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Breaking the Cycle of Congestion -An Extension Project Examining Traffic Congestion in Copenhagen

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Breaking the Cycle of Congestion

AN EXTENSION PROJECT EXAMINING TRAFFIC CONGESTION
IN COPENHAGEN

REPORT

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Worcester Polytechnic Institute

in partial fulfillment of the requirements for the degree of
Bachelor of Science

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Date:

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Preface

My name is Kevin Lee, a former member of an IQP team that worked with the Bicycle Innovation Lab in Copenhagen, Denmark in 2017. My teammates on that project were Sam Bickham, Alan Hunt, Adam Koubeck, and Sarah Stuart, and we worked as a team throughout the preparatory term and into the project term (from January to late March). In March, a family emergency developed back in the USA, which required my immediate attention and presence. I formally withdrew from the bicycle congestion project on March 21, 2017 in order to support my family. My advisers, Professors Lauren Mathews and V.J. Manzo, kept in frequent contact with me about possible next steps for the academic completion of my IQP. As the intended project term ended, an opportunity arose to continue my teammates' work. This report serves as a continuation of the original project (see Bickham et al., 2017), exploring aspects of the bicycle congestion issue that my teammates were not able to address due to time constraints.

Acknowledgements

In addition to the acknowledgements listed in page 1 of Bickham et al's (2017) report, I would like to extend a word of personal thanks to several people.

I would first like to thank my former teammates: Sam Bickham, Sarah Stuart, Alan Hunt, and Adam Koubeck. It was a great pleasure to work with each and every one of them in the short time I was able to contribute to their project. At the start of my extension project, they provided me with advice and helped me gather the data I needed to complete my project. This project would not be possible without them.

Additionally, I would like to thank Professor Lauren Mathews and Professor V.J. Manzo. Because of their hard work, I was able to begin my extension project. They offered comments and guidance to improve my project as well as gave insight in the moments I was unsure. The quality of work in this report would not be the same without their help.

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Introduction

Cycling is one of the most popular methods of transport in Copenhagen, Denmark. Over 675,000 bicycles exist in Copenhagen and that number is on the rise (C. Knudsen, personal communication, 2017). The large number of bicycles has a mostly positive impact on the city, as cycling promotes good health and reduces carbon emissions when compared to driving a car or using public transportation (Ministry of Transportation, 2014). The Copenhagen city council has introduced varied bicycle infrastructures in an effort to promote cycling, including spending over \$150 million in the past 10 years to expand bicycle lanes that currently measure 370 km in length (C. Knudsen, personal communication, 2017). According to Knudsen, estimates indicate that this strategy has been effective since 2010, with at least 56% of people in Copenhagen riding bicycles to work in comparison to 35% in 2010 (The City of Copenhagen Technical and Environmental Administration Traffic Department, 2016).

While the increase of cyclists is beneficial for personal health and environmental initiatives, the overwhelming number of bicycles has resulted in significant bicycle traffic congestion. In a report from 2016, bicycle congestion ranked as a major issue in Copenhagen for the first time (C. Knudsen, personal communications, 2017). With the bicycle lane overcrowding becoming a growing occurrence, cyclists have begun to ride outside of the designated lanes, causing frustration among motorists and pedestrians. The report also stated that bicycle accidents are at an all-time low, but cycling activists fear that if cyclists continue to act recklessly because of congestion, accidents might begin to rise again (C. Knudsen, personal communications, 2017). This reckless behavior has caused public opinion of cyclists in general to decline, and cyclists are being increasingly viewed as "egoistic, unaware, threatening and even dangerous" (C. Knudsen, personal communication, 2017). If this negative perception of cyclists were to continue, the goal to make 75% of all trips in Copenhagen in 2025 by bike, public transportation or on foot will be difficult to attain (City of Copenhagen, 2014). It is imperative to address the issue of bicycle congestion as quickly as possible.

Since bicycle congestion has only recently become a major problem, there is limited research examining the issue in Copenhagen. The City of Copenhagen's Technical and Environmental Committee published a report on an overview of Copenhagen's allocation of resources and the resulting projects implemented to increase cycling in Copenhagen with a concentration on accessibility for all, safety and security, and bicycle parking (The City of Copenhagen Technical and Environmental Administration Traffic Department, 2011). The report outlines the committee's objectives

and include plans to increase bicycle usage to 50% by 2025, while also increasing bicycle specific infrastructure by 35% (The City of Copenhagen Technical and Environmental Administration, 2011). The report also proposes increasing the width of bicycle lanes and implementing more bicycle specific infrastructure, such as bicycle bridges, to curtail the bicycle congestion in the city (City of Copenhagen Technical and Environmental Administration, 2016).

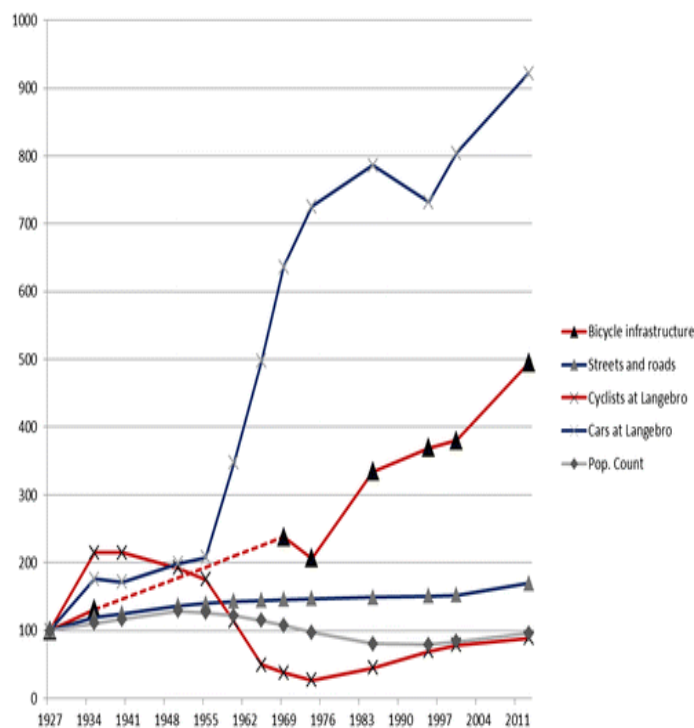
Copenhagen Cycling: A Brief History

The year 1910 marked the construction of the first bicycle lane infrastructure in Copenhagen. By 1912, bicycle lanes measured 35 kilometers of carriage tracks that the cyclists used to avoid the rough cobblestone pavement. Increasing automobile traffic caused concern among cyclists during the 1920s, which led to the separation of car and bike lanes through the use of dividers such as trees or curbs. This bike-car separation was the start of the “Copenhagen style” cycling infrastructure, allowing cyclists and automobiles to travel in their own dedicated spaces, rather than having cars and bikes drive in the same section of road (Carstensen, 2015).

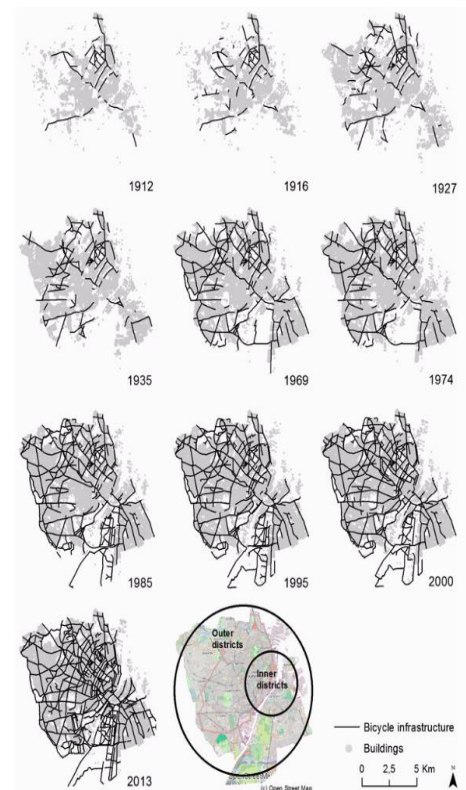
Historically, this expansion in biking infrastructure had significant economic impact. People could more readily cycle to jobs in the city, while residing in the low-cost suburbs surrounding the city. Oil shortages during World War II stimulated further expansion of bike infrastructure as bicycles became cheaper and thus a more preferred means of transport (Carstensen, 2015). The rate of bicycle infrastructure expansion declined during the 1950s and 1960s as restrictions on imports and fuel were lifted. The percentage of Copenhagen residents who used cars spiked from 24% to 46%, while the number of bicycle users in Copenhagen plummeted from 40% to 19% (Carstensen, 2015). Consequently, new infrastructure prioritized the increasingly popular automobiles with roadways modified to accommodate fewer cyclists. In some traffic intersections, bicycle lanes were removed entirely, forcing cyclists to share roads with motorists (Carstensen, 2015).

The Copenhagen cyclist organizations called out against the city’s automobile-centric focus. In the 1970s, the growing cost of oil caused by shortages made travel by car an expensive and, consequently, less popular transportation option. The priority of the Government of Denmark to build car-specific infrastructure decreased. By the 1990s, municipalities began investing in bicycle-exclusive infrastructure innovations. Dedicated bicycle lanes and infrastructure such as traffic lights and road markers were integrated with much of Copenhagen’s intersections and roads. Recently in 2010, the first bicycle superhighways were built. These superhighways travel from the suburbs and outskirts

of the city to major business, educational, and residential areas within the city with wider lanes and fewer required stops in between. This fluctuating investment in bicycle infrastructure is shown Figure 1a. The steady growth in biking infrastructure from 1912 to 2013 is represented in Figure 1b, as bike lanes are overlaid onto the map of Copenhagen. The 11-year period between 1974 and 1985 experienced the greatest increase in total length of dedicated bicycle paths, nearly doubling in size at a rate of nearly 9 km per year (Carstensen, 2015).



(a)



(b)

Figure 1a: Index numbers for kilometers of bicycle infrastructure and streets in Copenhagen over time, along with number of cyclist and car traffic over the Langebro Bridge, and the population of Copenhagen. 1927 is the base year. (Carstensen, 2015)

Figure 1b: Spatial development of the bicycle infrastructure in Copenhagen 1912-2013 (Carstensen, 2015).

Bicycles have become more widely used as a primary means of transportation in Copenhagen over the past two decades despite the decreasing cycling trend in Denmark as a whole (see Figure 2). Copenhagen has become a cyclist-centric city, with many major traffic intersections and roads modified with cyclists in mind (Carstensen, 2015). Certain intersections even have foot rests for cyclists waiting for the light to change and many stretches of roads have trash cans positioned such that cyclists

traveling down the road can easily throw away their trash. Today, 80% of the city's population either owns or has access to a bicycle as a result of this steady increase in bicycle investment over the past decades (Nielsen et al., 2013).

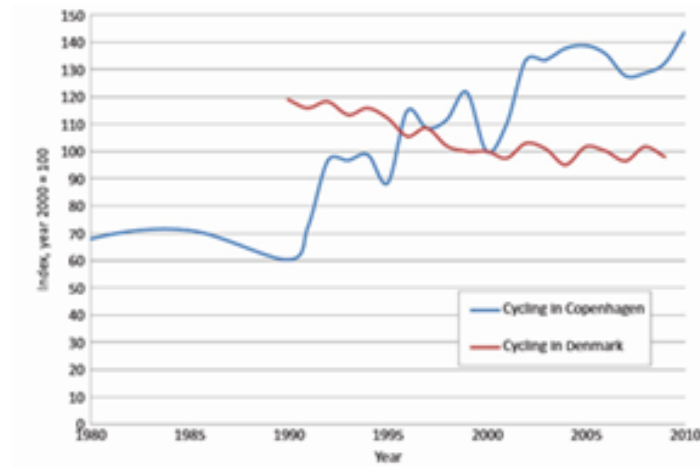


Figure 2: Index numbers for the number of cyclists in Denmark and Copenhagen. The data from 2000 is the base index (100 on the vertical axis) (Nielsen et al., 2013).

Bicycle Infrastructure in Copenhagen

The most common forms of bicycle transportation infrastructure in Copenhagen are bicycle lanes and bicycle tracks. Bicycle lanes are sections of the automobile lane shoulder that are dedicated to cyclist use with appropriate markings and white line dividers. Bicycle tracks are roads separated from automobile lanes either by dividers or by curbs (Jensen, 2008). In figure 3, the left picture shows a bicycle track, while right side picture shows a bicycle lane (commonly used in the United States). The city of Copenhagen also has rules that dictate how a bicycle lane should be marked and built in order to ensure safe traffic flow. Bicycle lanes require a minimum width of 2.2 meters and a maximum width of 3.5 meters, with the exception of narrow bicycle paths at 1.7 meters wide. Minimum lane width for motorist traffic lanes are 3.0 meters with typical dedicated bus lanes ranging from 3.25-3.5 meters (Focus on Cycling, 2013).



Figure 3: Photos of bicycle track (left) and bicycle lane (right) (Jensen, 2008).

Bicycle lane classifications further divide into shortened and advanced lanes, shown in Figure 4. Shortened bicycle lanes are mainly used in roads with fewer major intersections or one-way traffic (left). Advanced lanes use separation markings (dividers in some cases) and dedicated traffic lights for regulating traffic flow (right). The key difference is the dedicated traffic lights, which must be placed at a minimum height of 1.5 meters above the base of the main signal pole (Focus on Cycling, 2013).



Figure 4: Photos of shortened bicycle track (left) and advanced bicycle track (right) (Jensen, 2008).

Summary of Prior Results of Bickham et al (2017)

Due to time constraints, Bickham et al (2017) were only able to fully analyze two of the four selected intersections: The Dronning Louises Bro-Søtorvet and the Gothersgade-Øster Voldgade intersections. The Dronning Louises Bro-Søtorvet intersection (figure 5) is located at the outlet of a bridge with flared lanes on each road, with dedicated left and right turn lanes in each direction of automobile traffic. Northwest bound bicycle traffic shares the road with right turning automobile traffic, while all other directions of traffic have marked bicycle-only lanes.

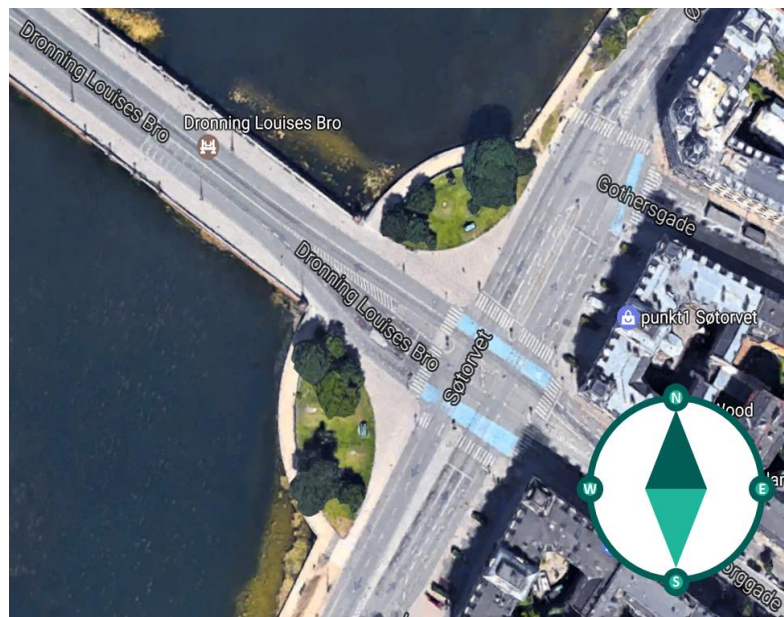


Figure 5: An aerial view of the Dronning Louises Bro-Sotorvet

The Gothersgade-Øster Voldgade (figure 6) is located in the inner city. Automobile traffic has dedicated turning lanes on all sides except northeast bound traffic which has neither right nor left turn lanes. Øster Voldgade has dedicated bus and bicycle lanes. Gothersgade does not have dedicated bus lanes, and cyclists must share the right turn automobile lane.

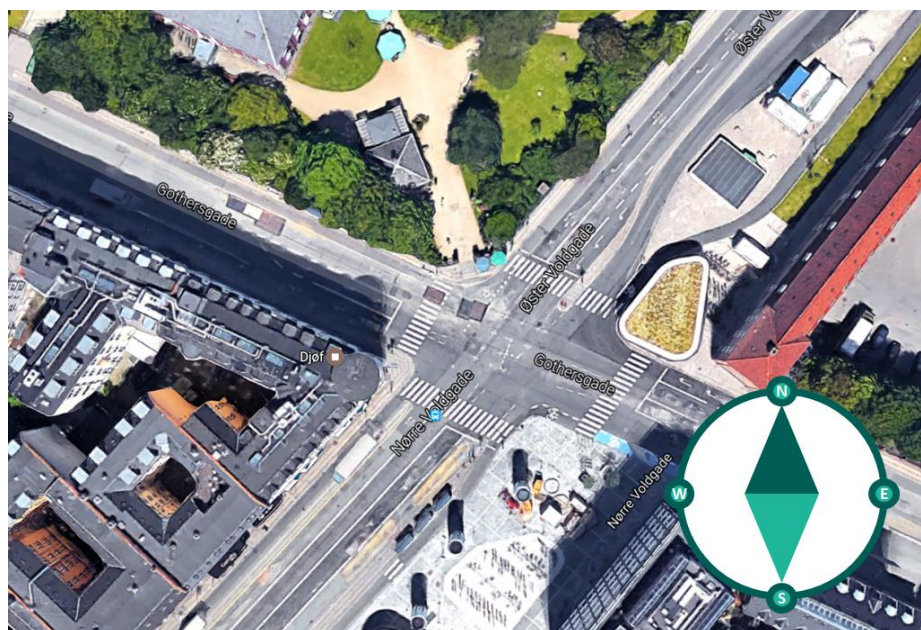


Figure 6: An aerial view of the Gothersgade-Øster Voldgade intersection

Bickham et al (2017) recorded both intersections during the morning and afternoon rush hours and calculated the average number of motorists and cyclists moving through the intersection during these times. They formulated potential strategies and interviewed various stakeholders to discuss the practicality of each strategy. They then took those strategies and modeled them in software to determine the strategy's impact on bicycle congestion. All details of each strategy tested as well as the methodology Bickham et al (2017) used starts on page 10 of their report. From the data they gathered, they concluded that modifying traffic light timings were the most viable solution to implement to reduce bicycle congestion in Copenhagen.

Methodology

Bickham et al (2017) modeled two 4-way intersections to analyze potential solutions that would reduce bicycle congestion in the Rosenorn-Alle and Aboulevard intersection, with possible application in other similar intersections. The goal of this project was to further assess the effectiveness of these potential strategies in a non-4-way intersection. In order to accomplish this, I established the following objectives:

1. Evaluate bicycle congestion in a non-4-way intersection in Copenhagen.
2. Evaluate the quantitative impact of alternative strategies on current levels of bicycle congestion at the intersection.
3. Assess the practicality of implementing the strategies predicted to be effective for reducing bicycle congestion.



To meet these objectives, I used several methods, one for each objective, to both gather and analyze data. The methods included a study on a non-4-way intersection in Copenhagen, the use of PTV Vissim traffic software to simulate various potential strategies, and interviews with traffic experts in government and non-government organizations. This section explains each method in detail.

Objective #1: Evaluate bicycle congestion in the Rosenorn-Alle and Aboulevard Intersection

Bickham et al (2017) conducted a case study of intersections across the city in the early stages of their project. Together, we identified four intersections that represented the various types of intersection in Copenhagen. The intersection selection criteria are explained in the methodology chapter of Bickham et al (2017).

I decided to study a non-4-way intersection while adhering to the selection criteria laid out by the group, so I chose the Rosenorn Alle-Aboulevard intersection. Figure 7 shows a picture of the layout of the intersection in Google Maps, with each direction of traffic marked by a colored arrow. Automobiles traveling northwest on Aboulevard are able to make a left turn onto westbound Rosenorn-Alle. All eastbound automobiles on Rosenorn-Alle merge with southeast Aboulevard automobiles traffic. Aboulevard southeast automobiles are not able to make right turns in this intersection. Bicycle traffic traveling northwest on Aboulevard and east on Rosenorn-Alle are able to turn left in dedicated turning lanes to cross the intersection. The travel path for cyclists crossing the intersection is marked by the dotted lines across each road. Both bicycle paths in the north and south of the intersection cross over pedestrian and automobile traffic in order to cross the intersection. Southbound cyclists coming out of the northern bicycle lane are able to turn right and travel along Aboulevard northwest or continue straight across the intersection. Cyclists that continue straight use the Aboulevard northwest cyclist left turn traffic light to cross the intersection. Similarly, northbound cyclists coming out of the southern bicycle lane are able to turn right onto Rosenorn-Alle eastbound or continue straight and cross the intersection. Cyclists traveling straight are guided by the Rosenorn-Alle eastbound cyclist left turn traffic light.



Figure 7: An aerial view of the Aboulevard-Rosenorns Alle intersection with labeled directional traffic flow and bike path entrance/exit locations.

Bickham et al (2017) video-recorded all four intersections they identified for further study before they concluded that time constraints would only allow them to analyze two of the intersections. Thus, I obtained the video-recordings they made of the Aboulevard-Rosenorns Alle intersection to analyze for this project during the morning and afternoon rush hours. Bickham et al (2017) gathered data over the course of two days. The last intersection Bickham et al (2017) video-recorded was not included in either of our studies.

From the videos, I recorded the same observations as Bickham et al (2017) in their study of the two other intersections. Page 11 of their report describes their procedure for recording as well as number of recordings.

Traffic light patterns

To capture the light timings needed to model the intersection, Bickham et al (2017) used the stopwatch function on their smartphones to record the duration of green, yellow, and red lights in each direction of traffic. They measured light durations three times in the hour to ensure consistency. Bickham et al (2017) described their methods for this analysis in page 13 of their report. The light timing data that was observed includes the lights which affect the bicycle paths.

Number of cyclists and motorists

To model the intersection, I needed to count the number of cyclists and motor vehicles going through the intersection over the period of observation, for each direction leading into the intersection and for each direction traveled out of the intersection respectively. In order to accurately count cyclists and motorists, I reviewed the video footage taken by my teammates, who used Go-pros and smartphone cameras to record the intersection.

I stored videos recorded in an external drive, organized by the person who made the recording, and the date and time the recording was made. I reviewed each video to gather the following data:

1. Total number of cyclists and motorists traveling through the intersection each direction during rush hour. Since this intersection includes two bike-only traffic roads, each bicycle path was observed as well.
2. Number of motorists and cyclists that turned left, right, or continued straight relative to their direction of entry into the intersection.

I used these data to model this intersection with traffic modeling software to test strategies for reducing traffic congestion.

Objective #2: Evaluate the quantitative impact of alternative strategies

In order to model the data from the Rosenorns-Alle and Aboulevard intersection, I used PTV Vissim software, a traffic modeling software tool, to create a simulation of the intersection. Bickham et al (2017) details the procedure for creating the simulation on page 15 of their report.

Once the intersection was constructed with the traffic data and light cycle timings gathered from the case study, I began to test how each strategy affected congestion within the intersection. I used several but not all of the strategies that Bickham et al (2017) used in their report.

The first strategy was to increase the width of the bike lanes. The increased space would theoretically allow more cyclists to flow through the intersection. The Rosenorns-Alle and Aboulevard intersection, especially the bike path located at the north and south ends of the intersection (see figure 3), which according to the Danish Traffic Design Rules has an exceptionally small width of 1.7-1.8 meters. I tested two different lane width

adjustments; the first increase was 0.5 meters in addition to the original width and the second increase was one meter in addition to the original width. Each change would be implemented across all bicycle lanes and paths of the intersection. The increase in bicycle track width would allow for more cyclists to travel through the intersection. This also means that during red lights, more cyclists can wait in a given space from the light, reducing distance of travel to move through the intersection. Total street width in the Rosenorn-Alle and Aboulevard intersection was not increased and the total number of lanes in automobile traffic stayed the same. This meant that each increase in bicycle lane width would result in a proportional decrease in automobile lane widths. I compared the original intersection simulation to the adjusted width simulations to compare changes in traffic flow. Note that in certain intersections, motorist traffic lanes might already measure at the minimum width allowed by Danish traffic regulations. In this case, the increase of bicycle lane width would end up removing a motorist traffic lane entirely. This possibility was not accounted for in the Rosenorn Alle-Aboulevard base intersection model. Further implications of this potential limitation was discussed in the discussion section of this report.

My second strategy was to modify the light timing in the intersection. Currently, the majority of green light time goes to the motorized and cyclist traffic travelling along Aboulevard. I tested the one of the two variations of this strategy described by Bickham et al (2017). The variation added 5 seconds of green light time to the road with the highest bicycle congestion. In the Rosenorns-Alle and Aboulevard intersection, the Aboulevard side has a higher average traffic flow in comparison to Rosenorns-Alle.

I also examined the predicted impact of these strategies in the future, as Copenhagen's population increases. I increased total traffic flow in the intersection by 17% to match the increase stated in the 2016 Bicycle Report projections. This assumes automobile and cyclist traffic will increase in direct proportion to the population. Note that this proportional increase assumes that all increases in traffic are even and consistent. According to Claus Knudsen, the most projected growth in Copenhagen is most likely to occur in Amager, where residential development is increasing. This would mean that the increase in Copenhagen's population would focus in the south where Amager is located (C. Knudsen, personal communication, 2017). However, I was not able to estimate accurately how the population's projected increase would affect the Rosenorns-Alle and Aboulevard intersection specifically.

I determined the effectiveness of each strategy by calculating the overall change in traffic throughput. PTV Vissim has a "data collection point" feature which can be placed at any position in the intersection and measures vehicles that pass through the

point. I placed data collection points at every direction of traffic (automobile and cyclist) and recorded the number of automobiles and bicycles traveling in each direction of the intersection. By comparing the number of vehicles recorded in the base intersection simulation to the number of vehicles in the modified intersection simulation, I calculated the percentage change of vehicles traveling in each specific direction. I repeated each simulation five times to calculate the average traffic flow change for each direction of travel through the intersection, separately for bicycles and automobiles. I then calculated overall traffic change as a percentage by using the average across each direction and comparing it to the average of the base intersection results with no modifications. Positive traffic flow changes indicate traffic flow has increased. In the same way, a strategy that resulted in overall decreased traffic flow would be considered to be a more ineffective solution. I also calculated motorist and cyclist traffic flow separately on each street and travel direction, and from that, calculated the average increase or decrease in traffic flow with each tested strategy.

As stated in Bickham et al (2017), the main focus for each strategy the team evaluated was change in bicycle traffic flow. However, it is possible that if the intersection is modified to accommodate more cyclist traffic flow, motorist traffic flow might become more congested as a result. Increased car congestion would lead to environmental issues such as air pollution because of idle fuel consumption. I used the outcomes of these simulations as the basis for discussions with professionals about the feasibility and advantages or disadvantages of each strategy, as described below in objective 3.

Objective #3: Assess the practicality of implementing effective strategies

To assess the practicality of the suggested solutions in non-4-way intersections, I conducted interviews with government and non-government organizations with experience and expertise in Copenhagen bicycle culture and city infrastructure. I consulted with professionals to gain insight into both how they interpreted the results of the data, as well as any implications, unaccounted for by the simulations, that each strategy would have for stakeholders. I presented the results from the PTV Vissim models to interviewees to provide a foundation for the discussion of each strategy. I contacted:

- **Klaus Bondam, Director and CEO of the Danish Cyclists' Federation.** The DCF is a non-political interest group dedicated to promoting bicycling and bicycle safety.
- **Flemming Møller, Danish Cyclists' Federation.** See above.

- **Morten Skou, Owner of Copenhagen Bicycles.** The Copenhagen Bicycles is a bicycle renting company that enables tourists and locals to experience cycling.
- **Jos van Vlerken, Project Manager for the City of Copenhagen Technical and Environmental Administration.** The City of Copenhagen Technical and Environmental Administration is one of seven administrations responsible for traffic and environmental legislation.
- **Helen Lundgaard, Senior Consultant at Capital Region of Denmark.** Helen works in regional development for the Capital Region of Denmark, which encompasses Copenhagen and surrounding areas.

I contacted this list of individuals because they were previously interviewed by Bickham et al (2017). This meant that each of the potential interviewees would be familiar with the project and would be more likely to participate in the interview. The interviewees consisted of individuals in private companies, non-government and government organizations. Together, they represented a broad spectrum of interest groups and could provide different perspectives on my strategies, as well as how the implementation of each strategy might affect cyclists in Copenhagen.

I contacted each interviewee via email to ask them for a second interview on bicycle congestion and scheduled a time that was convenient for the interviewee. These interviews, conducted by Skype, were semi-structured, which allowed for follow up questions and further discussion that could potentially yield additional useful information. I communicated with each interviewee via email or phone to schedule a time to conduct the interview. I sent each interviewee a document detailing the different methods and a condensed version of the modeling data results of the three intersections before the interview so that the interviewee was familiar with the intersections and data results before the interview began.

I conducted the interviews while taking notes on my computer, while simultaneously asking questions. Interview audio was captured with the interviewee's consent, and I transcribed the audio after the interview, with recordings saved in an external drive with the file name containing the name and date of interview.

For each interview, I began by introducing myself to the interviewee as a member of the bicycle congestion research group from Worcester Polytechnic Institute. I explained to them that I was conducting a follow up project researching the Rosenorns-Alle and Aboulevard intersection, and explained how the intersection I analyzed is very different from the intersections my former teammates had analyzed. I drew the interviewee's attention to the different geometry, different traffic turning options in

comparison to the other two intersections, and the bike paths located at the north and south end of the intersection. I then stated the mission and objectives of my project and explained the objective of the interview. Specifically, I told the interviewees that the goal of my project was to evaluate the suggested solutions compiled by my teammates to reduce bicycle congestion in Copenhagen, and explained how I used predictive simulation traffic software to test a number of strategies to reduce congestion in this particular intersection.

After I finished detailing the background information to the interviewee, I began recording the Skype call. I began by asking the interviewee for their name and what role they specialized in for their organization. I then informed the interviewee that they were currently being recorded. I stated that if they did not wish to be recorded, I would stop the recording and continue the interview verbally; I also stated that they may request to speak “off the record” in which case the recordings would be stopped and restarted to omit the interviewee’s name. I asked them if they had any questions about this process and if they wished to give me permission to record them. Depending on their response, I took the corresponding action and then continued with the interview.

I started the interview by summarizing the suggested solutions that Bickham et al (2017) implemented into their intersection models. I explained that the percentage changes of traffic flow in the tables of the background document represented the overall change in automobile or cyclist traffic when compared to the base intersection simulation. I then detailed which strategies I tested in the Rosenorn Alle-Aboulevard intersection. I presented the data of this intersection and explained the impact of each suggested solution on bicycle and automobile traffic. After asking the interviewee if he or she had any questions about the material I covered, I proceeded to the interviewee feedback portion of the interview.

I began this part of the interview by asking them how practical they thought each strategy was. I defined the level of practicality based on the cost of implementation, time investment required, the likely receptivity of both drivers and cyclists to each strategy, and political support. This meant that a method that is inexpensive, takes less time, is well received by stakeholders will be considered very practical. This question allowed each interviewee to give their feedback on each strategy based on their individual expertise and level of technical experience.

My second question shifted the focus towards the stakeholders that would be impacted if any of the strategies were implemented into the intersections. The simulation data from both the Rosenorn Alle-Aboulevard intersection and the intersections analyzed by Bickham et al (2017) suggested that increased bicycle traffic would result in

increased motorist congestion. I asked the interviewees if different groups of stakeholders such as cyclists, motorists, pedestrians and politicians would approve or oppose these changes in Copenhagen intersections, and for reasons why it would be the case. When it comes to changing intersections in Copenhagen, there are many individuals and groups that are affected by such a decision. The choice of whether to implement a certain strategy is not only affected by motorists and cyclists, but also affected by politics and the surrounding areas and businesses. After the interviewee responded, I asked them in what ways groups opposed to implementing these strategies could be accommodated. I asked tailored follow-up questions for further details after the interviewees gave me their initial response.

The third question I asked the interviewees was if there were any additional factors to consider when determining how each strategy affects cyclists, pedestrians, and automobiles. Although my previous question encompassed the stakeholders affected by implementing changes to the intersections, there might have been other factors that I did not take into account. The interviewees, with their expertise and experience, might have been able to explain additional factors that would affect the choice to implement certain strategies.

My fourth and final question considered everything the interviewee and I have previously discussed – specifically, which strategy did they think would be most effective in reducing bicycle congestion in Copenhagen? For the sake of this interview, an effective method was defined as strategy that improved traffic throughput and reduced congestion, specifically for bikes. An ineffective method was defined as a strategy that further increased congestion in the intersection.

I concluded the interview by asking the interviewees if they had any further questions, comments, or concerns. I reminded them that the content of the conversation was recorded, if they had given prior consent to do so. I thanked them for their participation and stopped the recording.

After I completed each interview, the audio file of the conversation was stored in an external USB drive with details on the interviewee's name and the date on which the interview took place. I listened to each interview file twice. The first time I listened, I took notes on main ideas and quotes from the interviewee. I kept track of how our conversation developed and paid close attention to the information each interviewee said. The second time I listened to the interview audio, I verified the progression of the conversation. I also checked for any additional information that was not noted in the first listen. I then began writing the transcript for the interview. Each interviewee had separate transcript files. The transcript document began with the interviewee's introduction and

from there detailed the interviewee's thoughts as he or she responded to each question. I marked the points where I asked new questions and recorded major points of the interviewee's response, as well as important statements.

Results

Objective #1: Evaluate bicycle congestion in the Rosenorn-Alle and Aboulevard Intersection

Rosenorn Alle-Aboulevard

Table 1 details the traffic light timings in the Rosenorn Alle-Aboulevard intersection. All light durations are measured in seconds with yellow light timings identical across automobile and cyclist traffic. Fields noted with “n/a” indicate that vehicles are not able move through the intersection in that specific direction. Directions of traffic which have light timings for both vehicle types indicates that both traffic types move through the intersection in that direction.

Table 1: Light timings for the Rosenorn Alle-Aboulevard intersection (in seconds)

| Light Timings (Seconds) | Green Light (Bicycles) | Green Light (Automobiles) | Red Light (Bicycles) | Red Light (Automobiles) | Yellow Light (Both) |
|------------------------------|------------------------|---------------------------|----------------------|-------------------------|---------------------|
| Aboulevard NW/SE (straight) | n/a | 64 | n/a | 32 | 4 |
| Aboulevard NW (left turn) | 18 | 28 | 78 | 68 | 4 |
| Rosenorn-Alle E/W (straight) | n/a | 28 | n/a | 68 | 4 |
| Rosenorn-Alle E (left turn) | 64 | n/a | 40 | n/a | 4 |

The data shows that light timings heavily favored the Aboulevard automobile traffic in both morning and evening rush hours. The Rosenorn-Alle traffic lights are green less than half the time that the Aboulevard traffic lights are green. Cyclists traveling parallel to the automobile traffic benefited from the same light timings as the automobiles. For cyclists crossing Rosenorn-Alle, they received much longer green times when compared to the cyclists crossing Aboulevard. With over 1000 cyclists traveling across the intersection in the morning and evening rush hours, congestion centered in areas where cyclists were waiting to cross the intersection, such as the Aboulevard northwest bound cyclists' left turn lane and the northern bike path cyclists. Figures 8 and 9 show the recorded number of bicycles and automobiles passing through the Rosenorn Alle-Aboulevard intersection during the morning and afternoon rush hours.

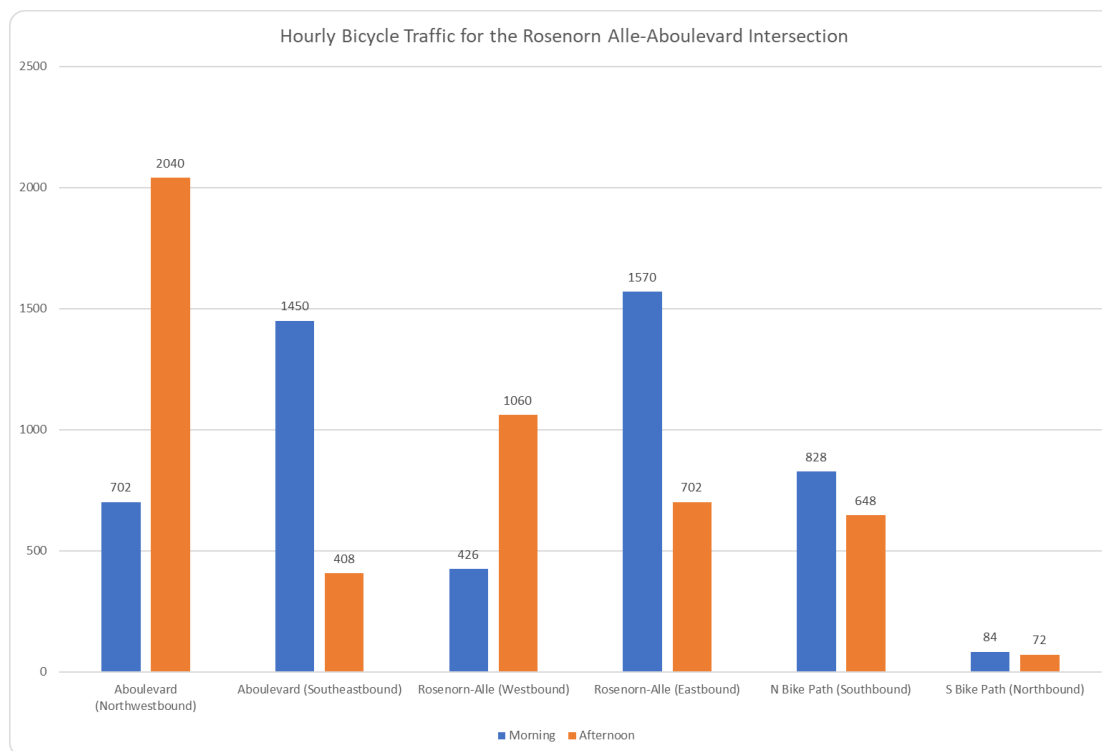


Figure 8: Recorded number of cyclists traveling through the different Rosenorn Alle-Aboulevard intersection directions during the morning and afternoon rush hours.

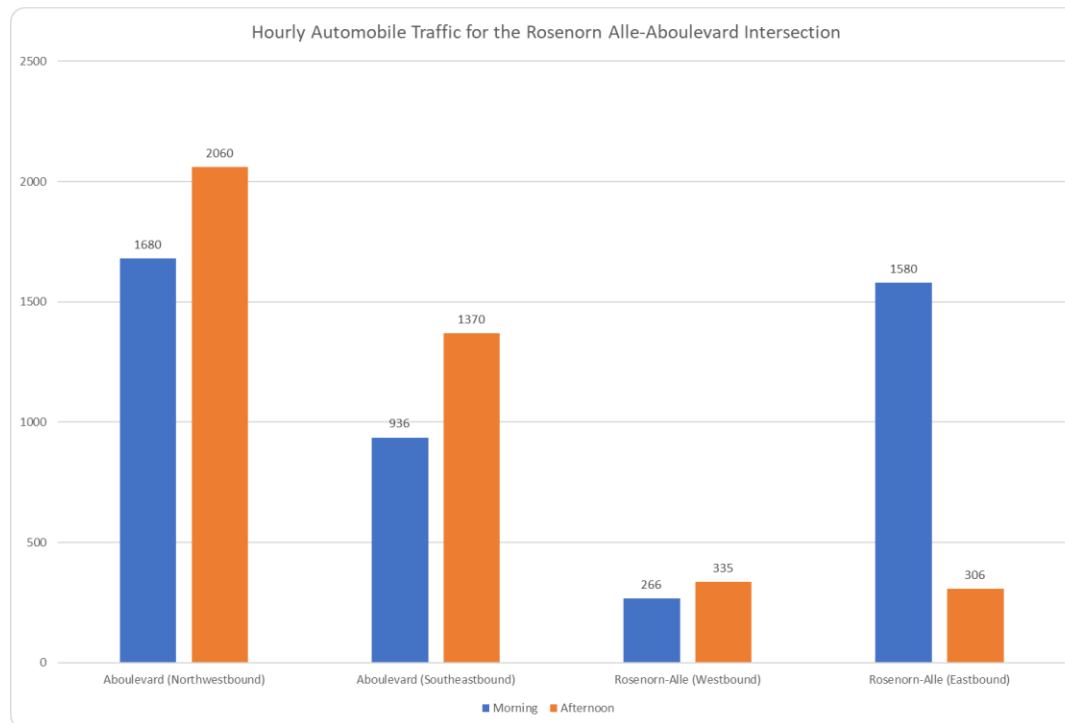


Figure 9: Recorded number of motorists traveling through the different Rosenorn Alle-Aboulevard intersection directions during the morning and afternoon rush hours.

Objective #2: Evaluate the quantitative impact of alternative strategies

I used the data from the video analysis of the Rosenorn Alle-Aboulevard intersection to model traffic using the PTV Vissim software. The number of automobiles and cyclists in the video data for morning and afternoon rush hours served as inputs for the base intersection model. From the base model, I was able to test strategies to reduce bicycle congestion in the intersection by modifying various intersection attributes, such as bicycle lane width and traffic light timings. The strategies I chose to implement were also previously tested by my teammates in the main report.

Figure 10 below shows the PTV Vissim model of the Rosenorn Alle-Aboulevard intersection. Blue lines indicate roads for automobiles and bicycle tracks for cyclists. Purple lines are called “connectors”, which indicate which directions a road can turn onto.

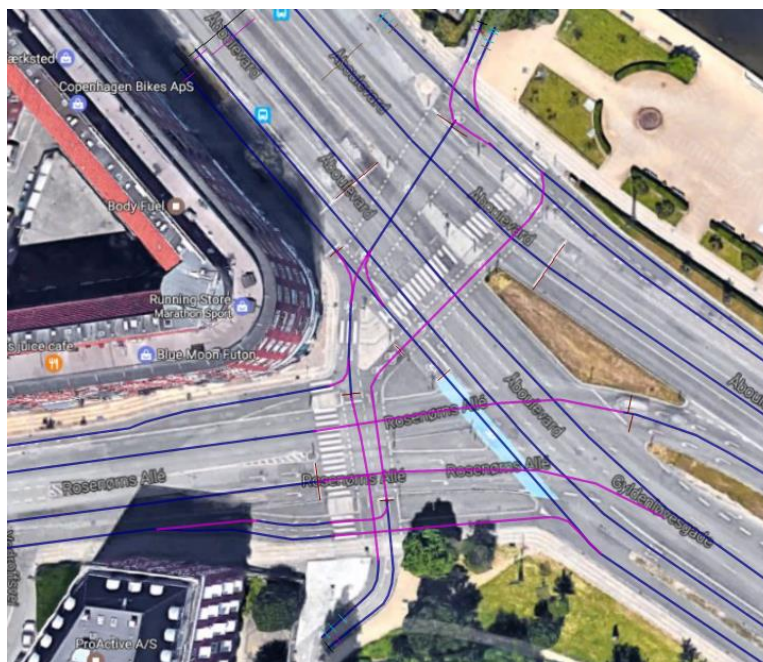


Figure 10: The Rosenorn Alle-Aboulevard intersection simulation in PTV Vissim

I tested the following strategies: increasing the width of bicycle lanes, modifying green light timing, and combining both of the previous two strategies. Similarly to Bickham et al (2017), I tested each strategy and variation of each strategy 5 times and calculated the average across them. I compared the results of the modified intersection to the results from the base intersection model data to produce a net percentage change in traffic throughput in each direction for automobiles and bicycles separately. All

directions of each form of traffic was averaged to produce an overall percentage change across the entire intersection. The base intersection simulation results are shown in figures 11 and 12 below, which show predicted traffic flow for both current population and projected population after a flat 17% population increase according to the calculations from the City of Copenhagen (City of Copenhagen Technical and Environmental Administration, 2016).

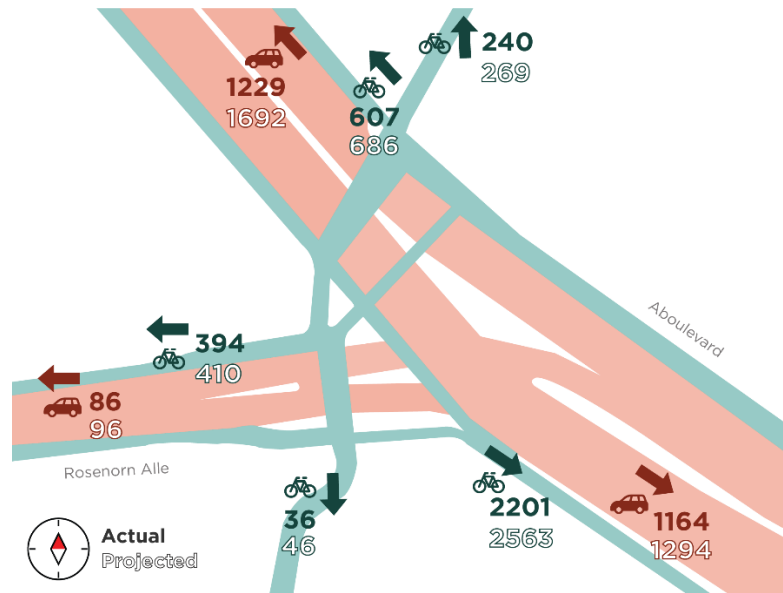


Figure 11: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Aboulevard intersection during the morning rush hour with no modifications. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

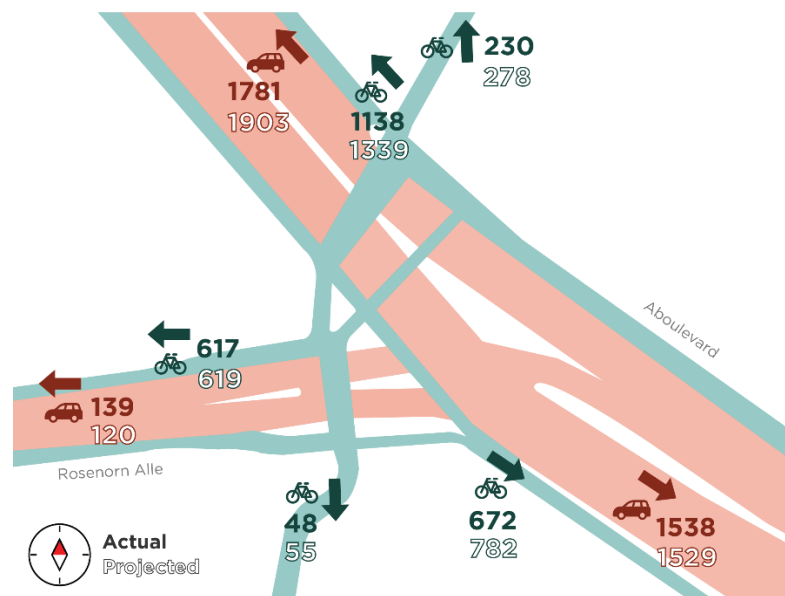


Figure 12: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Aboulevard intersection during the afternoon rush hour with no modifications. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

Increasing Bicycle Lane Width

I increased the width of each bicycle lane in two separate increments: 0.5 meter and 1 meter. PTV Vissim models automobiles and bicycle in different ways. In an automobile lane, only one automobile is able to occupy any given space. When a red light is present, automobiles stop within a fixed distance from each other, while bikes move to fill in space to maximize the number of cyclists in a given area. Thus, in car lanes, cars always travel in single file, whereas in bike lanes, bicycles may ride two or more abreast rather than in single file. Each variation was tested 5 times and averaged. I compared the average for each modification to the base intersection with no modifications to calculate a net percentage change in traffic flow for both cyclists and motorists. Figures 13-16 show the net changes in traffic throughput for both variations during the morning and afternoon rush hours.

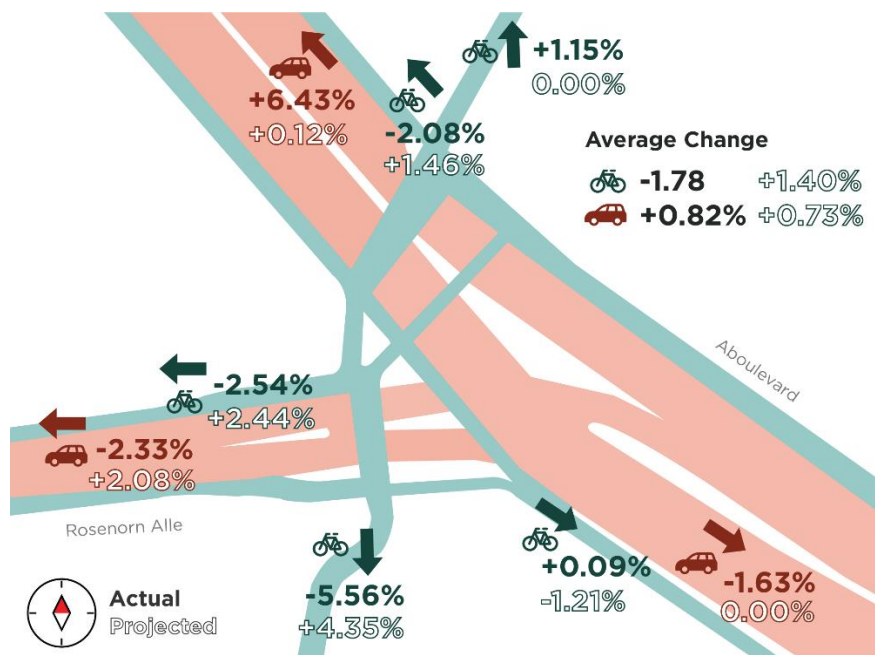


Figure 13: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Aboulevard intersection during the morning rush hour with a 0.5-meter increase for all bicycle lanes. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

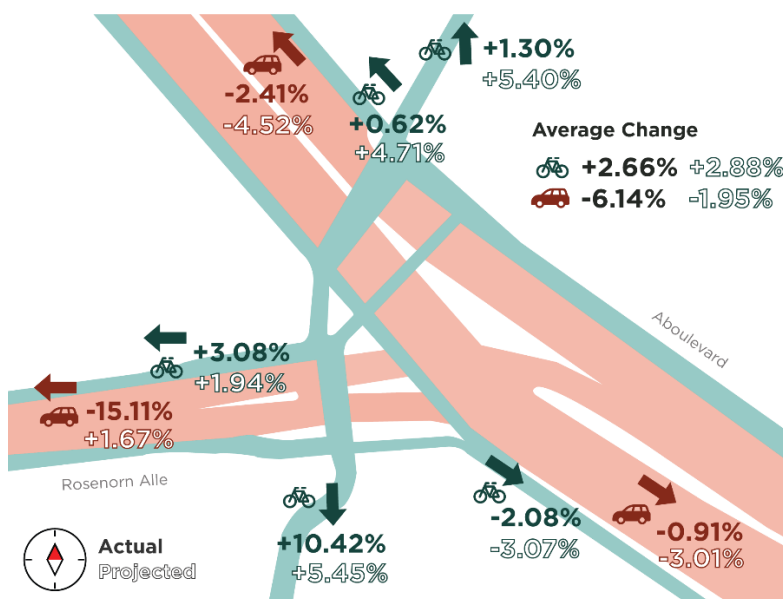


Figure 14: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Aboulevard intersection during the afternoon rush hour with a 0.5-meter increase for all bicycle lanes. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

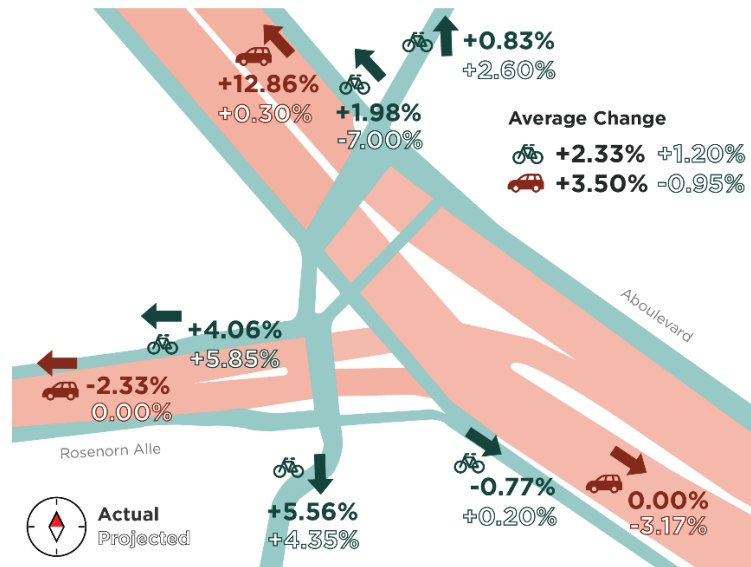


Figure 15: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Avenue intersection during the morning rush hour with a 1-meter increase for all bicycle lanes. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

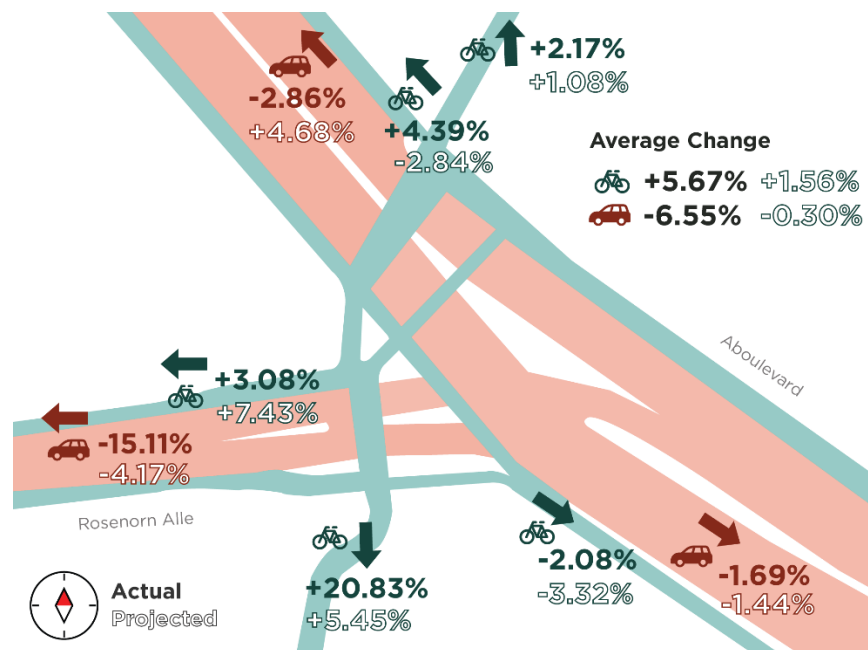


Figure 16: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Avenue intersection during the afternoon rush hour with a 1-meter increase for all bicycle lanes. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

Modifying Traffic Light Timings

I tested how the adjustment of traffic light timings affected traffic congestion in the Rosenorn Alle-Aboulevard intersection. First, I increased the Boulevard northwest bound bicycle left turn traffic light green time by five seconds, and second, I increased the Rosenorn Alle eastbound left turn cyclist light green time by five seconds. I chose to give five seconds to the left turn bicycle traffic signals because cyclists seeking to turn left have the shorted green light time. This short green window in combination with the large number of cyclists gathered at the traffic lights, especially on Boulevard, causes large amounts of cyclist congestion with little time to move all of them through the intersection. By contrast, cyclist traffic traveling parallel to automobile traffic have the longest green times, so no noticeable congestion occurs. Each variation removed five seconds of green time from the automobile lane of the other road to keep the overall light cycle time the same. I chose to keep the overall light cycle time the same to mitigate the impact this strategy would have on public transportation such as buses over long periods of time. Figures 17-20 show the net changes in traffic throughput for both variations during the morning and afternoon rush hours.

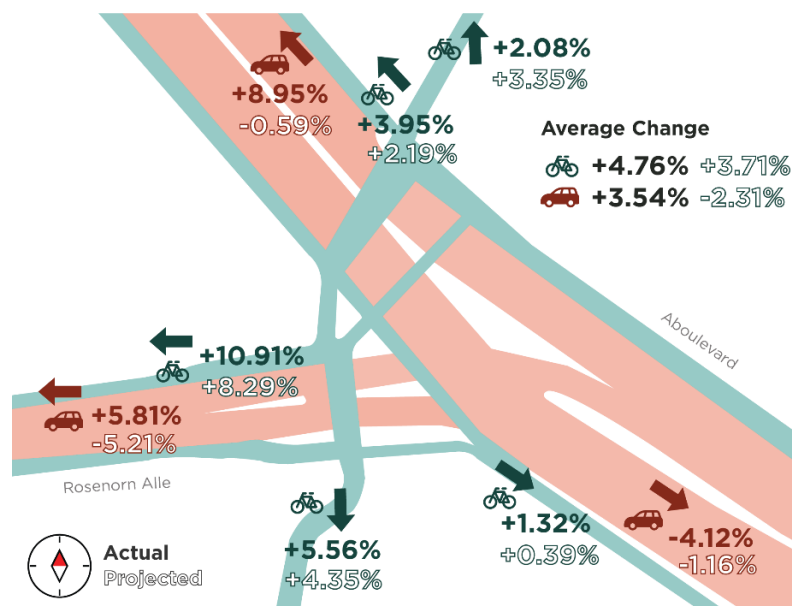


Figure 17: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Aboulevard intersection during the morning rush hour with a five second green time increase for the cyclist traffic lights on Boulevard. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

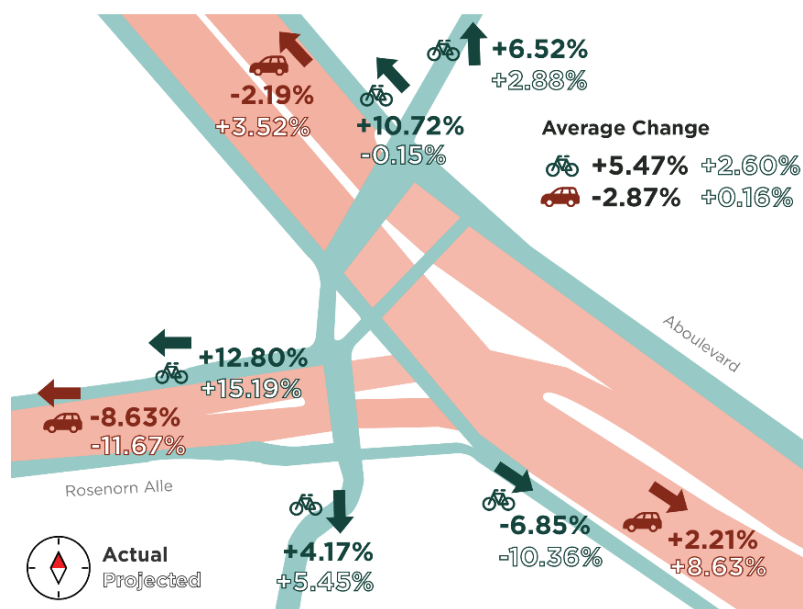


Figure 18: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Avenue intersection during the afternoon rush hour with a five second green time increase for the cyclist traffic lights on Avenue. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

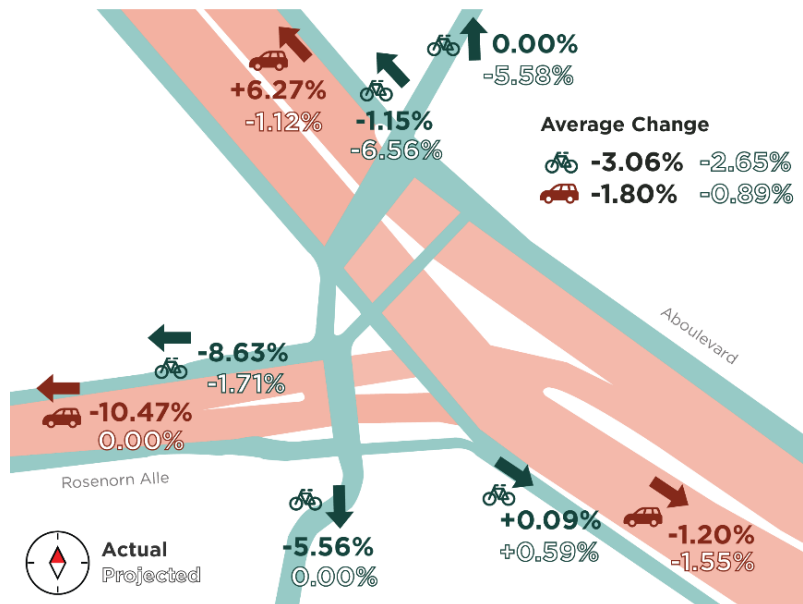


Figure 19: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Avenue intersection during the morning rush hour with a five second green time increase for the cyclist traffic lights on Rosenorn-Alle. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

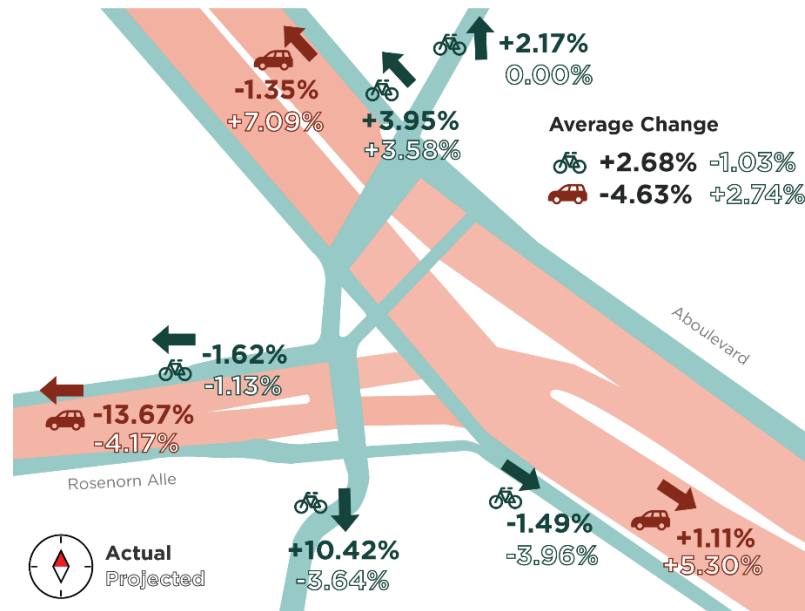


Figure 20: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Avenue intersection during the afternoon rush hour with a five second green time increase for the cyclist traffic lights on Rosenorn-Alle. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

Combining Strategies

I also ran simulations that combined both of the previous strategies: widening bicycle lanes by 0.5 meters and increasing cyclists' green light time by five seconds on one road. I tested two variations of this strategy. First, I increased the Avenue northwest bound bicycle left turn traffic light green time by five seconds, and second, I increased the Rosenorn-Alle eastbound left turn cyclist light green time by five seconds. Each variation removed five seconds of green time from the automobile lane of the other road to keep the overall light cycle time the same. All bicycle lanes widths were increased by 0.5-meters for both variations of the test. Figures 21-24 show the net changes in traffic throughput for both variations during the morning and afternoon rush hours.

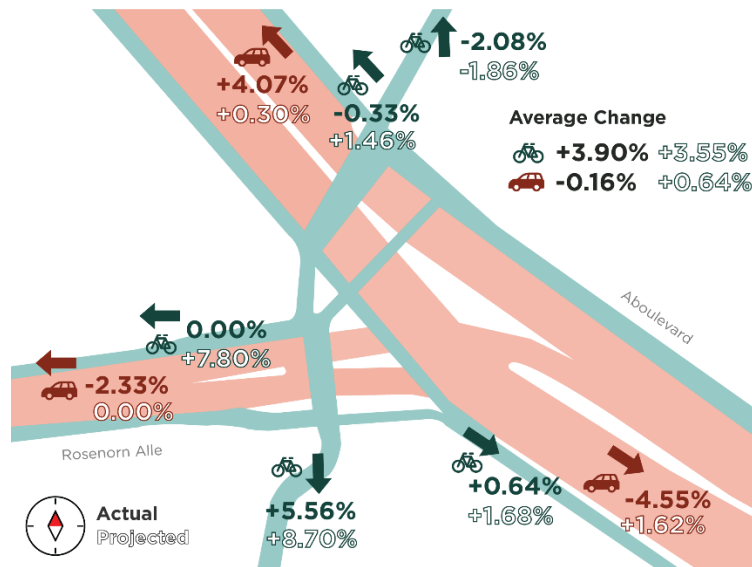


Figure 21: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Avenue intersection during the morning rush hour with a five second green time increase for the cyclist traffic lights on Avenue and a 0.5-meter increase for all bicycle lanes. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

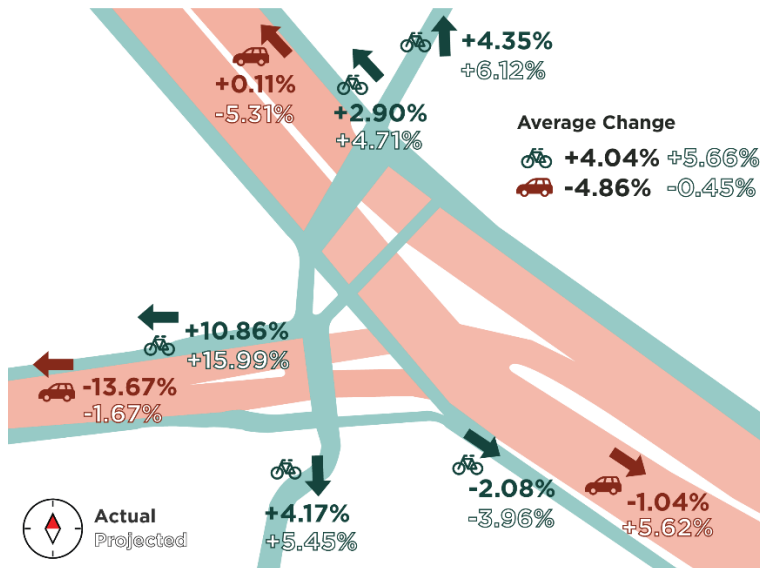


Figure 22: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Avenue intersection during the afternoon rush hour with a five second green time increase for the cyclist traffic lights on Avenue and a 0.5-meter increase for all bicycle lanes. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

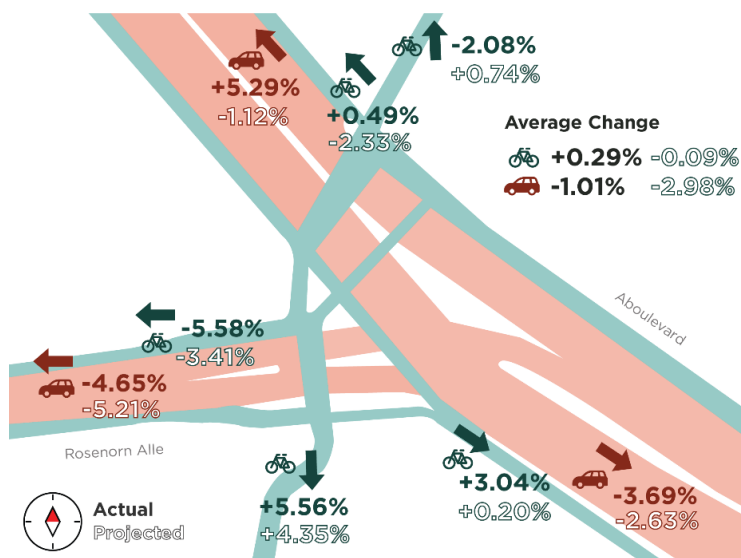


Figure 23: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Aboulevard intersection during the morning rush hour with a five second green time increase for the cyclist traffic lights on Rosenorn-Alle and a 0.5-meter increase for all bicycle lanes. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

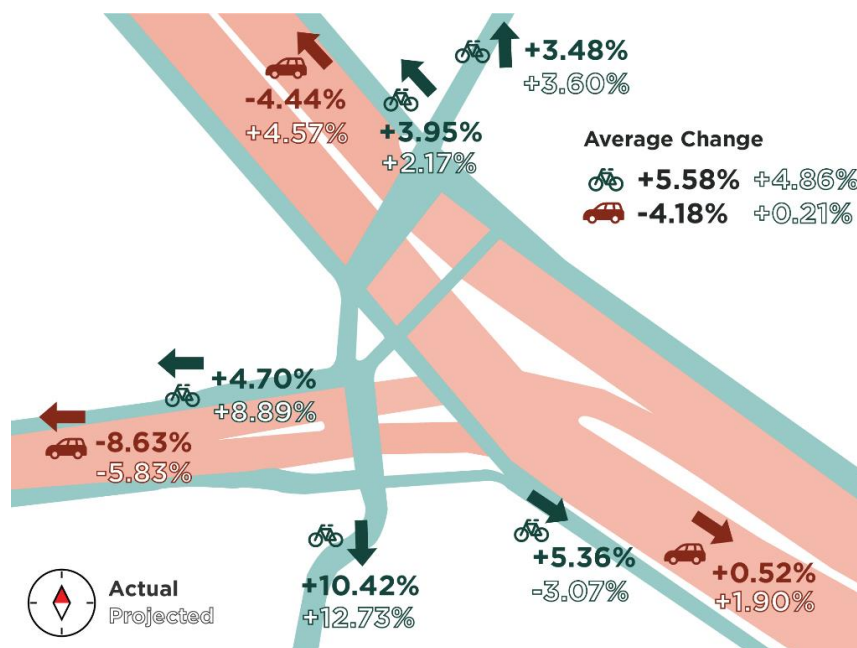


Figure 24: Model prediction numbers of automobiles and cyclists travelling through the Rosenorn Alle-Aboulevard intersection during the afternoon rush hour with a five second green time increase for the cyclist traffic lights on Rosenorn-Alle and a 0.5-meter increase for all bicycle lanes. For each direction, the percentages shown above in colored text indicate predictions based on models using current population size, while the percentages shown below in white text indicate predictions based on models using the projected increase of 17% in population size by 2025.

Objective #3: Assess the practicality of implementing effective strategies

I contacted the five individuals previously interviewed by Bickham et al (2017) for interviews. I received responses from three individuals detailed below.

- **Mr. Møller Møller, Danish Cyclists' Federation.** The DCF is a non-political interest group dedicated to promoting bicycling and bicycle safety.
- **Mr. Vlerken van Vlerken, Project Manager for the City of Copenhagen Technical and Environmental Administration.** The City of Copenhagen Technical and Environmental Administration is one of seven administrations and are responsible for traffic and environmental legislation.
- **Mrs. Lundgaard Lundgaard, Senior Consultant at Capital Region of Denmark.** Mrs. Lundgaard works in regional development for the Capital Region of Denmark, which encompasses Copenhagen and surrounding areas.

These interviewees are a part of various government and non-government organizations, with different levels of technical background. Before each interview, I sent a background information document to each interviewee which outlined both the intersections Bickham et al (2017) had analyzed as well as my own analysis of the Rosenorn Alle-Aboulevard intersection. I also included condensed tables that detailed the results of each tested strategy for each intersection. These documents can be found in appendix A. Each interviewee provided diverse perspectives not only on the practicality of each strategy but also what additional factors and groups would be affected through these changes.

I began each of my interviews by asking each interviewee what his or her thoughts on each strategy were in terms of practicality and effectiveness. This included the strategies tested by Bickham et al (2017) in the Dronning Louises Bro-Søtorvet and the Gothersgade-Øster Voldgade intersections. Mr. Møller noted that even though the cyclist right turn on red strategy was being implemented in certain areas of the city, he had some reservations on whether or not the strategy would have a significant positive impact on bicycle congestion, saying that "making it possible to turn right in a certain direction may cause trouble for those with crossways". He explained that cyclists in Copenhagen were already frustrated with other cyclists merging from the right and that this strategy might increase problems instead of solve them (Møller, personal communications, 2017). Both Mr. Møller and Mrs. Lundgaard were surprised that the simulation for right turn on red did not increase cyclist traffic in the definitive way they had previously hoped for (personal communications, 2017).

When discussing the strategy to increase bike lane width, all three interviewees agreed that the task would not be very practical. Mr. Møller stated that although widening bike lanes would be very effective in reducing bicycle congestion, the economic department of the municipality would not approve. Mrs. Lundgaard also believed that widening the bike lanes would be a “bigger exercise because of the required construction work” (Lundgaard, personal communications, 2017). Mr. Vlerken’s reservations towards this strategy were rooted in Danish traffic laws. Mr. Vlerken pointed out that both bicycle and automobile lanes had minimum width specifications that were documented in Danish traffic regulations. For bicycle tracks the minimum width is 2.5 meters while automobile lane minimum width is 3 meters. In the case of the Rosenorn Alle-Aboulevard intersection, automobile lanes had sufficient space for the bicycle lanes to be widened but Mr. Vlerken said that in areas that already have the minimum width for car lanes, increasing bicycle lanes would either force the total road width to increase, or remove car lanes entirely (Vlerken, personal communications, 2017).

All three interviewees agreed that modifying light timings would be the most practical solution. Mrs. Lundgaard stated that this strategy does not require the same physical work as the other strategies and can be implemented without much difficulty. Mr. Møller noted that modifying light timings would prove very effective and practical in areas with heavy motor traffic where pedestrian and “crossing cyclists get only 8-12 seconds of green time and a wait time of up to 140 seconds” (Møller, personal communications, 2017). Mr. Vlerken stated that modifying the light timing is easier to implement and is more commonly done in comparison to bike lane modifications, and believes the strategy would be viable in the city of Copenhagen (Vlerken, personal communications, 2017).

Mr. Møller said that reducing motor traffic by implementing strategies that favor cyclists does not necessarily mean that motor congestion will increase in that area. Mr. Møller pointed a legislative action that limited motorist traffic near Nørreport, and said that although many citizens were concerned that surrounding businesses would suffer and congestion would rise, car congestion remained at similar levels after implementation. Mr. Møller stated that motorists can “very quickly find other ways to get in and out of the city” (Møller, personal communication, 2017).

All three interviewees also spoke considerably on the political factors that influence the decisions to implement cyclist centric strategies. Mr. Vlerken and Mrs. Lundgaard claimed that even these types of decisions are almost entirely political. Mr. Vlerken asserted that the decisions to give or take lane space from cars depended mainly on the current political climate given that such changes were within legal limits. Currently, Danish politics are dominated by the party that tends to favor policies that

support cyclists and even though their majority seems strong, Mr. Vlerken speculated that it is possible that this majority might change, causing cycling infrastructure to become lower on Copenhagen's priority list. Mrs. Lundgaard added to my understanding of the Danish political system by detailing that the four municipalities in Copenhagen are responsible for the physical layout of local intersections, as well as light timings are determined on a local level. However, in cases such as light timings, municipalities often coordinate with each in order to maximize efficiency of traffic between them (personal communications, 2017).

Mr. Vlerken mentioned that politicians and other organizations are very aware of Copenhagen's increasing bicycle congestion issue, but said that when deciding which specific actions to take to reduce congestion becomes a more complex problem. Mr. Møller pointed out that an important factor in a person's choice to take a bicycle or a car is the cost and convenience of using a bicycle relative to a car. He claimed that this was the primary reason other cities in Denmark suffered a lack in bicycle use in comparison to motor traffic as no other city accommodates cyclists as much as Copenhagen does. Mr. Møller expressed optimism for increased cycling because public transportation is continuously becoming more and more convenient for the bicycle user (Mr. Møller, personal communications, 2017).

Mrs. Lundgaard also brought up bicycle theft as a personal reason she does not like using a bicycle to commute. She felt that in many areas of the city there was not adequate bicycle parking, which deters people from biking out of fear of theft (Lundgaard, personal communications, 2017).

Mr. Vlerken mentioned that there is an additional and very important component in the effort to change the political landscape for more cyclists. He said that Copenhagen cycling started as a grassroots movement that advocated safety concerns for automobiles and opposed economic dependence on oil. Because of their efforts, Danish politicians began taking legislative action to reduce automobile growth and increase focus on cycling infrastructure. He stated that citizen movements have played a "big role" in the infrastructural change in Copenhagen (Vlerken, personal communication, 2017). Mrs. Lundgaard asserted that the main solution to improving cyclist conditions was for the Danish people to invest in cycling initiatives and become more involved in advocating cycling.

Both Mrs. Lundgaard and Mr. Vlerken discussed Copenhagen as a model for other cities interested in expanding their city cycling. Mrs. Lundgaard that Copenhagen has a responsibility to continue advocating for increased cycling to set an example for other cities whose leaders seek to transition the population away from dependence on private automobiles. Mr. Vlerken also stated that Copenhageners "feel like [they] are

contributing something to the world which is a field of specialty in a way and it motivates [them] to keep pushing the technology and solutions. (personal communications, 2017).

Transcripts for each interview are available in appendix A of the report.

Discussion

Increasing bicycle lane widths by 0.5 meters had generally unremarkable results. After applying the flat 17% population increase, bicycle traffic showed a slight increase. By comparison, increasing the bicycle lanes by 1 meter had consistently better results for cyclists, with bicycle traffic increasing twice as much in comparison to the 0.5-meter increase. This increase in bicycle width would remove space from motorist lanes and hinder car traffic. By increasing the bicycle lanes by 0.5 meters, motorists suffered a slight decrease in overall traffic. All interview feedback suggested that committing to this strategy would be financially taxing, especially if implemented across many intersections. The construction required to implement the increases in bicycle width would hinder both car and bicycle traffic for the duration of construction. Political climate must also be taken into account. The Rosenorn-Alle and Aboulevard intersection, according to Jos van Vlerken, is a very motorist heavy intersection which would be difficult to change without significant political resistance.

Modifying light timing in the Rosenorn Alle-Aboulevard intersection was the most viable strategy, balancing effectiveness and practicality. Among the two variations, increasing the Aboulevard cyclist green time by 5 seconds produced the best results. Bicycle traffic increased considerably while motorist traffic decreased by only a quarter of the cyclist increase. Most motorist and cyclist traffic flow traveled along Aboulevard, which made the increase in green time for Aboulevard outperform the increase of green light time for Rosenorn-Alle. All interviewees agreed that this strategy would be practical to implement across many intersections without requiring as much financial or political resources.

This strategy combined both characteristics that benefit cyclists: bicycle lane width and green light time. By employing both methods at the same time, the resulting bicycle traffic increase achieved the highest consistent increase among all potential strategies. The most effective results came from adding 5 seconds to the Aboulevard cyclist light and increasing bicycle lane width by 0.5 meters.

From the results in their final report on the Gothersgade-Øster Voldgade and Dronning Louises Bro-Søtorvet intersections, Bickham et al (2017) concluded that the modifying traffic light timing strategy was the most viable strategy in the two intersections they analyzed. The adjusting bicycle lane strategy and combined strategy also had the same issues that I had mentioned previously. Although adjusting bicycle lane widths would improve bicycle traffic overall and allow more cyclists to travel through these intersections, the required roadwork combined with the detriment to traffic during

construction makes this strategy difficult to implement in many locations at once. Combining bicycle lane width adjustments with traffic light modifications bore different results. Implementing this strategy in the Rosenorn Alle-Aboulevard intersection produced the highest increase in cyclist traffic while also producing the highest decrease in motorist traffic. In the previous two intersections, Bickham et al (2017) found that implementing this combined strategy did not increase bicycle traffic significantly in comparison to changing only traffic light timing. Since this strategy was effective in the unusual Rosenorn Alle- aboulevard intersection but not in the more standard 4-way intersections analyzed by Bickham et al (2017), this suggests that this strategy might not be viable to implement across many intersections in Copenhagen.

Although my extension project followed similar methodologies to that performed by Bickham et al (2017), there were several key differences that distinguishes my project from theirs.

The first major difference lies in the intersection I chose to analyze. As I mentioned earlier, my choice to analyze the Rosenorn Alle-Aboulevard intersection stems from how different the intersection is designed from the previous two intersections observed by Bickham et al (2017). Both the Gothersgade-Øster Voldgade and Dronning Louises Bro-Søtorvet intersections are classified as 4-way intersections. Both motorist and cyclist traffic are able to turn right or left as needed, with dedicated left turn lanes for most directions of traffic. Traffic light timing in these intersections are also quite simple. One road will receive the green light, with a slight delay for motorist traffic, followed by the same for the other road. The Rosenorn Alle-Aboulevard intersection is structured very different in comparison, with bike paths in the north and south ends of the intersection and restricted motorist turning options. Rosenorn-Alle eastbound motorist traffic is required to merge into Aboulevard southeast bound traffic and the only turn motorists can make in this intersection is the left turn from Aboulevard northwest bound to Rosenorn-Alle westbound. Because of how the intersection is structured, cyclist traffic seeking to cross the intersection must cross both Rosenorn-Alle and Aboulevard and the bicycle traffic lights associated with them. This creates complicated traffic interactions and timings for both cyclists and motorists.

The second major difference was which strategies I chose to implement in the PTV Vissim traffic simulations for the Rosenorn Alle-Aboulevard intersection. I chose not to implement the right turn on red strategy and the right turn track strategy due to the geometry of the intersection. The idea behind right turn on red and right turn tracks is that, provided that the turn is safe to attempt, a cyclist would be allowed to turn right and continue traveling even though their respective traffic light is not green. In the Rosenorn

Alle-Aboulevard intersection, there are only two directions of traffic in which this turn on red would be applicable, Rosenorn-Alle eastbound turning onto Boulevard southeast bound and Boulevard southeast bound turning onto Rosenorn-Alle westbound. I did not test the right-turn on red strategy that Bickham et al (2017) applied to their intersections, because such turns are already legal for cyclists at the Rosenorn Alle-Aboulevard intersection.

Although PTV Vissim is a powerful tool that allowed Bickham et al (2017) and myself to model, modify, and test each intersection, the way in which the software represents each detail of the intersection may not completely match what happens in the real intersection. For example, in the Rosenorn Alle and Boulevard intersection, the Boulevard northwest bound cyclist traffic has a dedicated left turn which often becomes overcrowded as shown in figure 25.



Figure 25: Boulevard left turn cyclists waiting at a red light

In PTV Vissim, bicycles are programmed to fill in available spaces but keep a one-meter distance from other abreast cyclists at all times. In reality, cyclists may be more or less densely packed than the fixed parameter used by the software without extensive knowledge of the software to change these parameters. This is an example of how real intersection traffic interactions might differ from software simulated ones. Advanced interactions such as yielding, lane changing behavior, or varying levels of cycling experience might be common knowledge to a veteran Copenhagen commuter, but a computer simulation like those in the PT Vissim software might not allow the user enough flexibility to accurately model actual cyclist or diver behavior.

The PTV Vissim simulations were designed to only gather the number of cyclists and motorists traveling through each direction of a single intersection. Other variables such as average vehicle wait time and impact of each strategy on other intersections in the surrounding area were not evaluated. It is possible that a modification to one major intersection could impact the traffic flow in the surrounding area. Additional evaluation is

required to better understand how a specific strategy will impact intersections throughout Copenhagen.

Bickham et al (2017) and I interviewed various stakeholders with various levels of expertise in how each proposed strategy might impact specific intersection and surrounding areas. Most of interviewees focused on the social and political circumstances and impact that would influence the implementation of each strategy. Unfortunately, none of the individuals that were interviewed specialized in traffic design/engineering or worked directly with intersection modification. Although each interviewee contributed valuable information to help further understand the complex issue of bicycle congestion such as the social relationships between different forms of traffic and the different political agendas within the city of Copenhagen, specific quantitative information was lacking. Information such as how previous implementation of similar strategies impacted traffic or how changes to one intersection impacts the surrounding areas were not covered in detail. Interviewing an individual that specialized in traffic design would have been extremely helpful in understanding how the proposed strategies would specifically affect the intersection in question and the surrounding areas in both the short term and long term.

Conclusion

Based on the results from the collected data, I have found that modifying traffic light timings was the most practical strategy while being effective at the same time. Only modifying traffic light timing is cost-effective, and can be implemented in any intersection or area where bicycle congestion is growing. With everything considered, both from simulation results and interviewee feedback, I believe that this strategy has the best balance of effectiveness and practicality for implementation across Copenhagen to reduce bicycle congestion. Further information, including additional quantitative analysis and stakeholder perspectives, should be included in any final decisions about how to manage traffic congestion at these and other intersections in Copenhagen.

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Appendix A: Interview Summaries

Below are the summaries for each interview I conducted. In the cases which the interviewee requested certain sections of the conversation not be included in the main report, those sections have been removed from the transcript.

Summary of Skype Interview with Flemming Møller

Interviewee: Møller, Flemming

Friday, 23 June 2017 11:00 – 11:45 (00:45:56)

Cyklistforbundet (Danish Cyclists' Federation)

Rømersgade 5-7, 1362 Copenhagen K

Interviewer: Kevin Lee

The interview recording began with some technical difficulties with the Skype video call. Audio was present but video was not, and after a minute of technical difficulties, I and Flemming Møller agreed to keep the conversation audio only. Flemming Møller began the interview by asking several questions about the background information I had sent him a few days earlier. He first asked about what date and time in which the intersection was recorded during the original project period (March – May). I clarified the time period of time in which all video data was collected and that all simulated result tables were based on model projections from the original video data. I Lee then introduced himself as a member of the bicycle congestion research group that partnered with the Bicycle Innovation Lab to research bicycle congestion in Copenhagen. He informed Flemming Møller that he was conducting a follow up project that analyzed the Rosenørn-Alle and Aboulevard intersection and pointed out the differences between this intersection and the intersections that his teammates had analyzed previously. Flemming Møller interjected with a question about the bicycle paths in the north and southern ends and if the video data accounted for cyclists travelling to and from that direction to which I clarified that it did.

I formally asked for consent to both record the audio interview as well as cite the information discussed during the interview. Flemming Møller gave his consent and introduced himself as a member of the Danish Cyclists' Federation for 25 years who was responsible for overseeing cycling related events throughout the year. I returned to Flemming Møller's previous question and explained that the tables in the background information document was a condensed net change in cyclist and motorist traffic, and

that the number of cyclists moving in and out of both bicycle paths were recorded in a more detailed spreadsheet. Flemming Møller then asked about the current vs projected populations and which time period was the basis of the estimated population increase. I pointed to a document published by the City of Copenhagen's technical and environmental department that estimated a total of 17% increase in bicycle traffic in 2025. I explained that this estimate was used as the projected increase in order to simulate future population conditions. Flemming Møller asked how the pedestrian and automobile lanes would be affected by the bicycle lane increases to which I responded that the increase in bicycle lanes would result in a proportional decrease in the overall automobile lane widths, which would keep the total lane width the same. I noted that the right turn on red strategy was not implemented in the intersection he was analyzing stating that:

"I have established that the intersection I have chosen to analyze is more complex in certain ways when compared the intersections that my teammates analyzed. I believe that in applying the same strategies that my teammates did on this 3-way merge might be able to produce different results than my teammates and how it would impact intersections of unusual geometry such as this (Rosenorn-Alle and Aboulevard) one. You will notice that I did not implement a right turn on red or right track strategy in this particular intersection... for automobiles, automobiles are limited to turn only in one direction which is the Northwest bound Aboulevard traffic turning left onto Westbound Rosenorn traffic".

Flemming Møller commented that "it is a seldom thing to do. They (automobiles) would have turned earlier if they were traveling in this direction from the northwest. You could say the same thing about cyclists. They do not feel like they are turning right, for example. They come from the south from the lake and it is not felt like a right turn. It is more like a direct forward running".

I then ask:

1. "Now that you are able to see the data from the previous two intersections as well as the more unusual 3 lane merge intersection, in terms of implementation of each strategy, how practical do you think each of these strategies would be. For the sake of this interview practicality would be defined as time investment, financial investment, public reaction, and from an organizational and political standpoint how practical would each of these strategies be?"

Flemming Møller started his response saying that the City of Copenhagen had already begun to implement right turn on red for cyclists in certain areas with the

cooperation of the municipality and the local police force. Although he was certain that this solution would be cheap to implement, “looking on the figure which you have collected, feels no surer that it would be very good because you have noticed in your measurements that making it possible to turn right in a certain direction may cause trouble for those with crossways. We have heard from cyclists especially that they are very annoyed with these cyclists coming in from the right without noticing anything. It’s a problem”. Flemming Møller expressed that he felt that widening the lanes would be more effective, but was not often implemented since it would be very expensive. He stated that “it would be quite tedious for the economical department of the municipality to just make all of the bicycle lanes broader here and here, so I think we will see more red right turns”. I asked Flemming Møller what he thought on the practicality of changing the light timings for the intersections so that they favor cyclists more and he responded that it would be possible to do this as long as the automobile traffic did not fall over 20% of the current motorist traffic throughput. Flemming Møller pointed out that certain intersection gives only 8 seconds for traffic to move in a single direction, so increasing the green time by 10 or even 12 seconds would greatly boost the traffic throughput of those particular intersections. He said that “it would be my advice to do this, especially in places where cyclists tend to cross over very motor heavy traffic... the problem is still existing that cyclists that have to cross these motor heavy intersections may wait 140 seconds before they can move. It is too much”.

I asked about the bicycle path widths in the north and south ends of the Rosenorn-Alle and Boulevard intersection. He drew attention to large amounts of traffic but comparatively narrow amount of road space available to cyclists. Flemming Møller commented that in places like the northern bicycle path the path is very narrow and it often caused trouble for cyclists that make left turns and cyclists traveling along Boulevard.

With his response concluded, I asked second question:

2. “So, for the future population increase, which was labeled as “Projected population”, what was implemented in software was a flat 17 percent increase in both motorists and cyclists traffic to see how each strategy would perform under a more intensive load of traffic in both categories. This would assume that traffic would increase proportionally across all areas and in identical ways to each other. What other factors goes into understanding more about how traffic increases would affect intersections that implement these strategies?”

Flemming Møller began by recalling a recent development near the Nørreport train station in which the municipality wanted to cut down on motor traffic in the area.

Many were anxious about this idea because they believed that the lack of motorist traffic would detriment local businesses in the area and hurt labor possibilities in the surrounding stores. Flemming Møller commented that “it showed up that motorists very quickly found other ways to get in and out of the cities. So, you had motor vaporization, and the motor traffic was diminished automatically in order to get faster in and out by the use of other ways. So, you cannot neglect even for Aboulevard that this could also be the situation. For instance, instead of 17% increase then you might have no increase at all but an increase in bicycle use in over 20 percent”.

I moved onto his 3rd question:

3. “So, in your opinion in these additional factors of residential development and traffic changes, do you think there are other factors that might we might not be able to simulate such as bicycle culture or the political change. Do you think there are any other factors that would affect cyclists and motorists in these intersections that we are not aware of currently?

Flemming Møller responded first by stating that “it would be difficult to point to certain definite things but we have noticed that the in the last 2 decades that the price of using 1 or more ways of commuting do have a significant influence on the peoples’ choice and is why many other parts of Denmark suffer from a lack of bicycle use in comparison to motor traffic use”. Flemming Møller emphasized that the commuter weighs the cost of public transport with the acquisition and fueling of a vehicle when deciding what method of transport to use. I asked about how difficult it was to acquire an automobile considering that the tax for cars is quite high. Flemming Møller acknowledged that it was quite high in comparison to surrounding countries, but was still lower than what it had been in the 1990s. Flemming Møller commented on the appeal of owning a car stating that “Many do it because they are young families so they have children they have many tasks they have many things to go to and come from so it is difficult to transport small children in bicycles, and many do and you can see that special bicycles that support small children are coming forwards”.

I asked his final question:

4. “Considering all the things that we discussed with the practicality and the raw results, do you feel like there is a particular strategy that you would lean towards in terms of support and in terms of how the public would receive it?

Flemming Møller noted that the government, municipality, and other political figures all want cycling to continue to prosper. He stated that it was very exciting to have bicycles compatible with other forms of traffic such as taking bikes onto trains and buses.

Flemming Møller said that the strategy he most preferred was “definitely the change of light timing. I am convinced because of your work that the effective way to make it easier for all pedestrians and bicycles to get through the traffic is to modify the light timings. It is cheaper than widening the bicycle lanes”.

I recalled that Flemming Møller had sent an image of a colorized LED sign for cyclists that displayed traffic congestion in further intersections. I commented that he had seen implementation of this concept in a larger scale in Shanghai, China where signs there would have colorized maps that would account for 1 or 2 kilometers ahead, but was implemented only in motorist traffic. Flemming Møller explained that these signs are intended to help cyclists plan their route more effectively by notifying areas of congestion and in the future maybe even construction or other hazards. The city of Copenhagen is planning to add 4 of these types of signs into high traffic areas of the city and Flemming Møller says that he is eagerly awaiting the results of this change.

I concluded the interview by reminding Flemming Møller that the conversation was recorded and may be cited in the final report. He asked if he has any further questions or concerns about anything they had previously discussed. Flemming Møller asked if the additional green time for cyclists would be proportionally removed from the automobile green time to which I responded yes.

The interview concluded.

Summary of Skype Interview with Helen Lundgaard

Interviewee: Lundgaard, Helen (Chief Consultant)

Monday, 26 June 2017 11:00am -12:08pm (01:08:23)

Capital Region of Denmark

Nordre Frihavnsgade 106, 2100 København Ø

Interviewer: Kevin Lee

I began the interview with a brief introduction as a member of the bicycle congestion research group. He explained that he was working on an extension project in exploring how previously suggested strategies impact intersections of more complex structures or different geometries. I asked Helen Lundgaard to state her name and described a bit about her expertise and her field of work and asked for formal consent to recording the interview conversation as well as to use what was discussed in the final report. Helen Lundgaard verbally gave consent to recording the interview and to use her statements in I's report and explained that she worked in the capital region of Denmark, which was one of five regions in Denmark. She worked in a regional development department which included cycling development. She took a pause in her statement to clarify that she was a strategist not an engineer, and so would not be the best person to seek technical answers from. I responded by saying that all perspectives on this issue of bicycle congestion were important not just engineers' and that understanding the political, economic, and developmental side of this issue was very beneficial. Helen Lundgaard commented that all of the research conducted by I and his group was centered in the City of Copenhagen, which is one of 29 other municipalities in the region, and that her perspective was more regional in scale. The particular municipality that she worked in was one of the norther suburbs of Copenhagen, where many people there also use cars, bikes, and public transport to commute to work every day.

I moved on from the introduction into a brief background on his extension project, where he drew Helen Lundgaard's attention to the four-way intersections that his teammates previously analyzed. I pointed out that the Rosenorn-Alle and Aboulevard intersection has not only a different geometry but also had more complex routes with the inclusion of the northern and southern bicycle paths. I then asked his first interview question:

1. "With the documents, I have sent to you, and the number of strategies that were listed such as increasing all bicycle lane widths by 0.5 and 1 meter, adding five additional seconds to bicycle traffic on one street, and hybridizing the two, I wanted to discuss how practical each strategy would be in your opinion from a regional perspective. From your personal opinion, how practical do you think each strategy is?"

I clarified that how practical a strategy is will be defined as a combination of financial cost, time cost, as well as public and political reception. Helen Lundgaard started her response from the financial perspective, stating that although she was not aware of the financial costs associated with changing traffic lights, she did mention that the required investment and cost of widening bicycle lanes would be troublesome. She said that "I think broadening the lanes would be a bigger exercise because of the required construction work. Modifying light timings would require less physical work... I think changing the traffic lights would be easier... but sometime you need to do difficult things to get the right result". Helen Lundgaard noted that the simulation data of combining both strategies seemed to suggest the greatest positive impact, and also briefly mentioned that the Rosenorn-Alle and Aboulevard intersection was located near the border of two different municipalities. She made the statement that "when the city of Copenhagen wants to do something beneficial for cyclists at the expense of cars, it creates a big conflict with neighboring municipalities. So practically I think is one thing and politically is another. So you might get some angry mayors". She went on to recall that the city of Copenhagen once wanted to expand the parking strategy for bikes and received backlash from neighboring municipalities. She commented on this balance of favoring cyclists and cars saying that "those on the other side [people who drive cars] they will be the ones that feel the changes most, but I think sometimes things do hurt in order to get the solution we want, and you can't avoid if some things cost money or if it will be a problem for a certain time". Helen Lundgaard explained that these decisions were very political if you want to implement solutions that would have a substantial impact on either form of traffic, and went on to say that she was not fully aware of all the implications of each strategy on an economic scale. I asked further about the Danish government and the political aspects of this issue saying:

2. "I am not very familiar with how the politics in Copenhagen work, but are the municipalities themselves responsible for the street development of their own region and when you said there would be angry mayors then can those mayors say no to certain plans to change roads or intersections like the one in Rosenorn-Alle?"

Helen Lundgaard hesitated and said that the mayors of each municipality cannot necessarily refuse the higher government of Copenhagen. She told an example from May 2009. She said that “During this time there were discussions of implementing a congestion ring around the city and it became such a big ordeal because the mayors of Copenhagen were very angry because it would affect their geographies and citizens... this was such a big thing that it became an issue on the state level and in the end, it was dropped”. The Rosenorn-Alle intersection, Helen Lundgaard described, was under municipality authority and she made the distinction that some roads and intersections are owned by the state while most if not all others were governed by the municipalities. I asked for clarification on what was the distinction of state controlled and municipality controlled. Helen Lundgaard responded that roads under state authority were routes such as highways, bridges, and certain other roads which are only available to cars. Helen Lundgaard stated that there are only two levels of authority: local and state. She said that her department, which was responsible for 29 municipalities, does not have much say in what is implemented by the state. I asked if traffic light timings were also determined on the local level to which Helen Lundgaard says that they most likely are, but in many cases, they coordinated with other municipalities to make the intersections efficient.

I shifted focus from this topic by asking another question:

3. “I wanted to shift from this topic to the relationship between cyclists and automobiles. When Claus initially spoke to our group about this issue he mentioned that automobiles and cyclists, especially during congestion, have tension between them... What is your perspective on the interactions on automobiles and cyclists? How do you see it from your perspective?”

Helen Lundgaard started off by saying that she agrees with Claus and that as congestion increases you will have more of this tension. She says that this tension is present as well in areas outside of Copenhagen, and it is particularly large towards cyclists that use racing bikes. She says that “it makes things uncomfortable for the children and old people and slow people. They feel unsafe when there are not only cars but also fast bicycles”. Helen Lundgaard noted that she herself spends most of her commuting on a bike, and that this was mainly a cultural question. She wondered that if certain strategies were implemented in a particular intersection, how other parts of the city could be affected. She expressed that these changes could cause entire stretches of road to become congested, but she clarified that this was just speculating. Helen Lundgaard went on to say that “most would say that politicians would like to make things easier for bicyclists without bothering other people, and that would be preferable. But in

reality, you can't just use magic. There is a limited amount of space and if you give some to bicycles then you naturally have to take some from the others". I brought up the bicycle report document published by the city of Copenhagen Technical and Environmental Department. In it, I noted that the city of Copenhagen wanted to push for an increase in commuting bicycle percentages from 35% currently to 50% by 2025. I pressed further into this train of thought and asked:

4. "My next question for you is: with the way things are right now trying to make things easier for bicycles without harming automobile traffic too much, do you feel like at some point the city won't be able to do this anymore if they want to push for more bikes"?

Helen Lundgaard asked for clarification if the statistic for commuting bicycle percentages was based on cyclists inside of the city or if it included cyclists that moved in and out of the city each day. To answer this question, I began retrieving the document in question. Helen Lundgaard interjected during this, saying that there are many automobile owners that also ride bicycles frequently. She said that "It is not always that the motorists do not understand what the bicycles say, because many people one day go in a car and other days go in a bicycle". I confirmed that the statistic included cyclists traveling in and out of the city. Helen Lundgaard said that it is very brave that Copenhagen is pushing towards this vision and that in the municipality that she lives in there is a strong support for increase cyclist development. She acknowledged that it was difficult to encourage people living outside the city to use bicycles, but the super cycle highways that the city of Copenhagen developed showed that the city cared very much about cycling in places outside of Copenhagen. She stated that "their [Copenhagen's] traffic problems are not local, they are created regionally. The origins of their congestion like cars for example may be a regional one".

As Helen Lundgaard finished her response, I asked:

5. "For the groups that would be opposed to pushing towards a cyclist centric future, would there be any way to accommodate all groups while at the same time encouraging more cycling and less automobiles?"

Helen Lundgaard responded that she was sure that there were ways in which opposed groups could be accommodated. She speculated that there could be a number of incentives which could help those who do not use bicycles. Those who do not use bicycles primarily most likely have a good reason for doing so, and she joked saying that if people sent more money, than more people would be happy. She explained that people needed to invest into bicycle development in order to see more real change in

the city's infrastructure. She said that “you could speak to people's health and get healthier to live longer argument. It is not easy to argue that people will save the planet if they cycle in the next 50 years. So, the argument from a personal health perspective would be a more relevant topic to discuss. There is not just one thing that will win people over. There will be a range of solutions to be placed all across Copenhagen. Just like how you combine certain strategies some strategies would work better in different places in Copenhagen”. I moved onto his next question and asked:

6. “I wanted to talk more about the support politically and financially for increase cyclist development. I know you said that you are not an expert on the economic cost and effects of this but how do you think the support is right now for bicycle development for say the politics or the budget in Copenhagen?”

Helen Lundgaard pointed back to Copenhagen's past bicycle development saying that she believed that the city of Copenhagen really wanted to push for more cyclists. Helen Lundgaard then said “They can always do more, but the municipality of Copenhagen is doing the most in terms of setting aside the most resources and funding for infrastructure. They have a whole program dedicated to improving cycling conditions. There is no other city in Denmark that does this”. Helen Lundgaard stated that big discussion in Copenhagen currently was over parking space, and the recent talks to remove some city automobile parking in favor of cyclist parking spaces. Helen Lundgaard explained that there is a large international interest in Copenhagen because of their efforts to increase cycling priorities. She felt like Copenhagen had the responsibility to continue to move forward with a cyclist vision because they set the example for other cities around the world. I asked his final question:

7. “After all that we have discussed, are there any additional factors that we have not yet considered when understanding how a strategy would affect pedestrians and automobiles?”

Helen Lundgaard brought up a personal example saying “in the past half year, I have had 5 bicycles stolen... this is not everywhere, but you live in a place where there are no possibilities to check your bicycle. It is so easy for professional thieves to take bicycles from people. It is the main factor that influences whether or not I should take a bicycle in the city... it may be an issue with parking”. I asked for clarification on how bicycles are normally protected against theft such as through locks, parking racks and the like. Helen Lundgaard said that normally people would just lock up the bicycle. She compared cars and bikes saying that because bikes are smaller and so easy to grab, theft for bikes becomes easier and harder to track.

As the interview closed, the conversation shifted back towards the strategies simulated and the results of each strategy on the intersections. Helen Lundgaard noted that right turn on red surprisingly did not have any significant changes on the intersections. She also pointed out some large differences in the morning and afternoon simulations for certain strategies. I asked her if there was anything she had comments or concerns on. She said that there were still many things that might not have been factored into the simulations such as pedestrian routes and irregular bicycle behavior. She ended her response on a comment saying “The numbers can't lie, but the statistics are never the full story”. After I thanked her for her time, I concluded the interview.

Summary of Skype Interview with Jos van Vlerken

Interviewee: Van Vlerken, Jos (Project Leader)

Tuesday, 27 June 2017 6:45am – 7:45am (1:00:32)

City of Copenhagen Technical and Environmental Administration

Njalsgade 13, 2300 København S

Rømersgade 5-7, 1362 Copenhagen K

Interviewer: Kevin Lee

The interview began with some technical difficulties while setting up the Skype video call. I began the interview by asking Jos van Vlerken for verbal consent to both record the interview as well as use the information discussed in the final report. Jos van Vlerken agreed to both but asked to check over the interview transcript before using it in the final report so that he could clarify or correct any information that might have been misinterpreted. Jos van Vlerken commented on the noise around him and got up to find a quieter room. The Skype call briefly dropped as he relocates and connection was reestablished.

Jos van Vlerken introduced himself as a sociologist that worked for the City of Copenhagen as a project manager. He oversees smaller pilot projects that has a high degree of citizen evaluation. Jos van Vlerken clarified that he is not a traffic engineer or an expert on intersection planning but was very willing to offer what insight he could. I replied saying that the simulations run using video data of each intersection did not encompass all sides of the issue, and that the simulations might suggest something that in reality would not be received well by the public.

I moved on to explain the background of the extension project and how he chose to analyze the Rosenorn-Alle and Boulevard intersection because of its different geometry and increased traffic complexity in comparison to the intersections that his teammates analyzed. He clarified that the net change in traffic shown in the simulation result tables took the average of percentage changes across all directions of traffic within the intersection. Strategies used in the Rosenorn-Alle intersection was taken from the strategies used to analyze the previous two intersections. I clarified that the lane width modification strategy did not increase the overall width of the street, but took a small amount away from the car lanes. I talked further about the strategies that were implemented as well as detailed certain areas of the result tables. Jos van Vlerken asked I if he had sent the Rosenorn-Alle intersection analysis result document to him but later

found the document. For the next several minutes of the interview, Jos van Vlerken and I looked over the Rosenorn-Alle intersection results document as I explained details about each strategy such as how much was taken from the car lanes for each modification and how much green time was added to the bicycle traffic lane and how it affected other directions of traffic.

I then asked his first question:

1. "I have sent you these result documents so that they would serve as a foundation for this discussion. So, for each of these methods, lane modification and light modification, how practical do you think each strategy is? Practicality will be defined as time investment, economic investment, and public and political reception".

Jos van Vlerken began his response by giving his opinion on the bicycle lane modification strategy. He pointed out that bicycle lanes were often thinner in width going into the intersection than the bicycle lanes that moved through the intersection. He speculated that widening bicycle lanes would make sense since it would eliminate the congestion that was associated with transitioning from a wider bike lane to a smaller one. Jos van Vlerken pointed out that the decision to take space from the cars and give it to bikes was a purely political one, and depended on the political consensus at the time. Currently, there was a "left wing majority" and Jos van Vlerken believed that it may stay that way for a time, but commented that if a socio-democrat majority were to achieve majority, bicycle infrastructural expansion would be a lower priority. Looking at the Rosenorn-Alle intersection, Jos van Vlerken noted that the southeastern bound Boulevard traffic was a very popular route since it connected the north of the city all the way to the southeast parts of the city. Jos van Vlerken asked for clarification on the lane modification methodology and how space was taken from automobile lanes and given to cyclist lanes. I explained that as the bicycle lanes are increased, the overall width and number of lanes would stay the same. Jos van Vlerken expressed disagreement if this strategy was universally applied saying "that won't go well because those are the rules of the Danish traffic laws... If they are the minimum width specified, then you would be forced to remove car lanes... what you give to the cyclists depends on what you take from the car lanes, not so much the other way around". Jos van Vlerken commented that during rush hour periods, all three of the analyzed intersections were known to reach past their intended capacity, and that the decision to modify the intersection to favor cyclists more would be a political decision. Even though these kinds of modifications have been performed in the past on other intersection, Jos van Vlerken believed that

lane modifications would not be approved in the Rosenorn-Alle Aboulevard intersection specifically, or at least for a while.

Jos van Vlerken stated that modifying the light timings would be easier to implement. He mentioned that these kinds of modifications were performed more commonly than physical intersection constructions and was not as political as adjusting bike lane widths. In many intersections such as the Rosenorn-Alle intersections, cars were prioritized over cyclists but retained a compromise between the two. This meant that while cars are more favored, their light timings still accommodated cyclists as well. Jos van Vlerken stated that “We do not make it fit perfectly for cars and always find some sort of compromise between cars and bikes where cars have a higher priority but not a total dominance of the intersection”.

Jos van Vlerken mentioned that there were also laws which dictated how pedestrians should cross intersections. It was important that pedestrians are able to cross the entire intersection inside of their given green light time frame and not wait for too long between green times. In terms of the different modes of traffic, Jos van Vlerken said that “These two are of course opposing principles. You don’t want people to wait but you also want them to cross the whole intersection while the other direction waits. There is always a balance”. He went on to emphasize that intersection lights should not make people wait for green lights for too long saying “Remember that waiting time plays a role not only for pedestrians but also for cyclists. It is our experience that if you wait for too long, you are more likely to cross over when it is red. To lose your patience to cross while it is dangerous and illegal is very bad. It’s all about keeping waiting time as low as possible while still having enough time for pedestrians and cyclists cross... I definitely think that modifying the green light timings while taking these things into account would definitely be viable in Copenhagen”.

After Jos van Vlerken’s response, I shifted the conversation towards the stakeholders that would be affected by implementing strategies to increase bicycle traffic. He asks:

2. “I wanted to ask about the different groups behind these kinds of decisions. You mentioned that it was very politically decision. In terms of Copenhagen’s vision to push for more cyclists from 35% to 50%, what groups would and would not approve of these strategies to prioritize bike more and more and how can we work to accommodate these opposing groups?”

Jos van Vlerken responded by detailing the groups that approved of these cyclist centric changes. The left-wing parties and other cyclist organizations are the main

driving forces for these changes. Jos van Vlerken stated that “We can’t have more cars. That’s a fact of the matter really. Congestion can’t get bigger so the only solution is to have more bikes. Taking into account the population increase in the next 10 to 20 years. It is an understood fact, but it all comes down to the specific planning of corridors and roads to have a larger number of cyclists. It is easy for everybody to agree that congestion is a big problem, but it is harder to agree that congestion consists of motorists which we should try to have fewer of”. Jos van Vlerken explained that politicians understand and recognize this issue, but focusing on specific solutions becomes harder because it directly affected people. 60% percent of the population of Copenhagen commuted to work every day. Jos van Vlerken noted most commuters were coming from the surrounding municipalities and used more cars travel to work in comparison to those living in Copenhagen. Businesses would also be affected by such changes, since businesses required delivery transportation. Jos van Vlerken named some of these stakeholders such as the Danish cyclist federation, pedestrian federation, industrial union, and motorist federation which Jos van Vlerken explained must be taken into account. He commented that “there is starting to become a consensus that all unnecessary motorized traffic should switch to bicycles. Necessary automobiles would consist of things like business delivery services and other relevant services. And through the decreasing of congestion, these motorists would be able to travel in the city easier”.

Currently, Jos van Vlerken explained, the city of Copenhagen determines how each road will be divided among cyclists and motorists. This decision is revised every 5 years as traffic trends change. Traffic light timings are also changed to reflect any changes in vehicle prioritization. Jos van Vlerken also mentioned that there was also a bicycle program under the Technical and Environmental department that focused on locating and improving faults in bicycle infrastructure in Copenhagen. I then moved onto his next question:

3. “I kind of wanted to talk about the tension between cyclists and other modes of transportation. My sponsor Claus mad it very clear that there is a sort of competing tension between automobiles and cyclists and it seems like everyone mostly agrees. I am wondering what is the relationship between pedestrian and cyclists in these intersections?”

Jos van Vlerken responded that although there was generally more conflict between cyclists and automobiles, there was also some tension between cyclists and pedestrians. Jos van Vlerken said “When bicycles cross the streets or sidewalks it creates some annoyance in the pedestrians. But the term conflict has been a very vaguely defined term. Is it a conflict if someone on the street shouts at you? Does there

need to be a collision? I would say that acting out and shouting should constitute as conflict in some way". Jos van Vlerken began speaking on the distinctions between cyclists and automobiles as a form of transportation. "Cyclists have a better view of the world. They can slow down much faster than cars can so they are much more flexible in an urban environment... pedestrians and cyclists more or less move around each other more easily whereas cars are much more rigid... Motorists cannot see the world around them as much as cyclists and pedestrians can. Injuries to pedestrians are far more serious involving automobiles than for cyclists... cyclists are an annoyance, but cars are a risk".

I asked his final question:

4. "In your opinion coming from your administration, do you think there are any other additional factors that determines how a strategy is implemented other than what was previously talked about"?

Jos van Vlerken pointed to how Copenhagen cycling started as a grassroots movement. It began as a reaction against a highway building plan that would cut through the city. According to Jos van Vlerken, during that time period the only viable means of transportation was by car, which was combined with safety concerns from parents and an economic overdependence on oil. Jos van Vlerken stated that because of this movement, future legislation decisions changed. Jos van Vlerken said "There was a great grassroots movement that influenced the decisions that city hall had made and influenced decisions that they made moving forward. So I definitely think that citizen movements play a big role".

Jos van Vlerken began talking about Copenhagen cycling as an international influence. He said "When we go out to conferences, we feel like we are contributing something to the world which is a field of specialty in a way and it motivates us to keep pushing the technology and solutions. We want to stay at the forefront of this development. I think a lot of cities will start taking up biking again, but when other cities have bike lanes like Copenhagen then what do we have then? We need new solutions will help create more modal shift and more cyclists".

I concluded the interview by asking Jos van Vlerken if he had any question, comments, or concerns. I clarified that the interview was being recorded and cited in the final report. After confirming this, I ended the interview.

Appendix B: Background Information Documents Sent to Interviewees

Bicycle Congestion Background Information Document

My name is Kevin Lee, a member of the Bicycle Congestion Research Group along with Sarah Stuart, Sam Bickham, Adam Koubeck, and Allan Hunt. During our time in Copenhagen (March-May 2017), we observed the Gothersgade-Øster Voldgade, Dronning Louises Bro-Søtorvet, and Rosenørn Alle-Aboulevard intersections. A Google Maps image of each intersection is shown below.

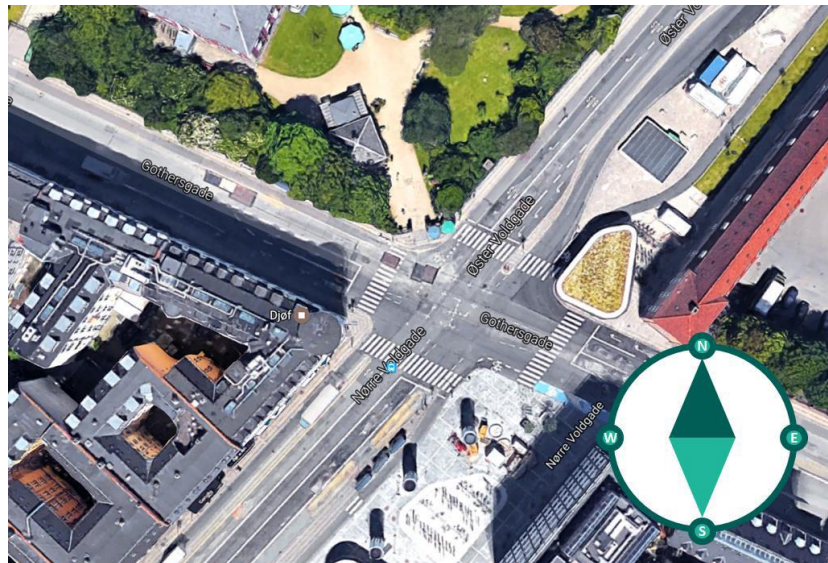


Figure 1: ..The Gothersgade-Øster Voldgade intersection

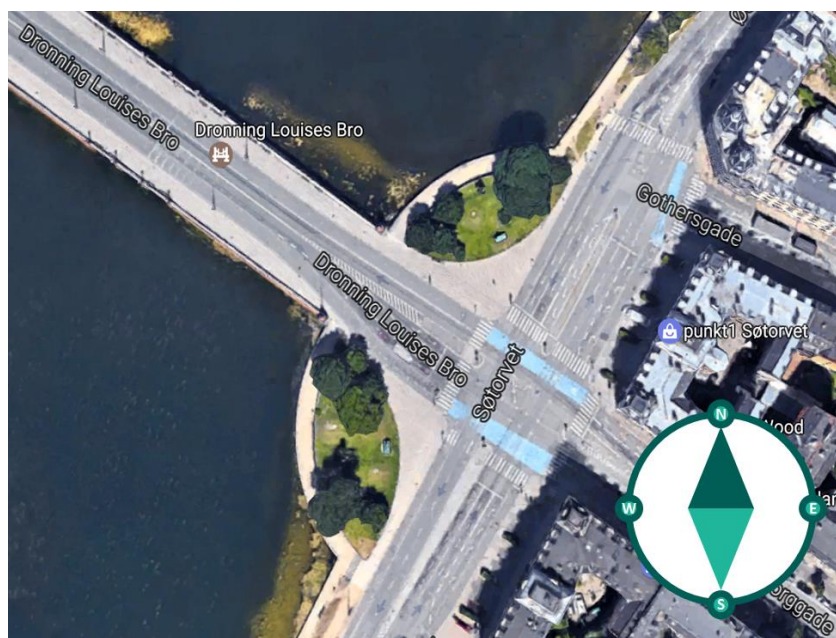


Figure 2: The Dronning Louises Bro-Søtorvet intersection

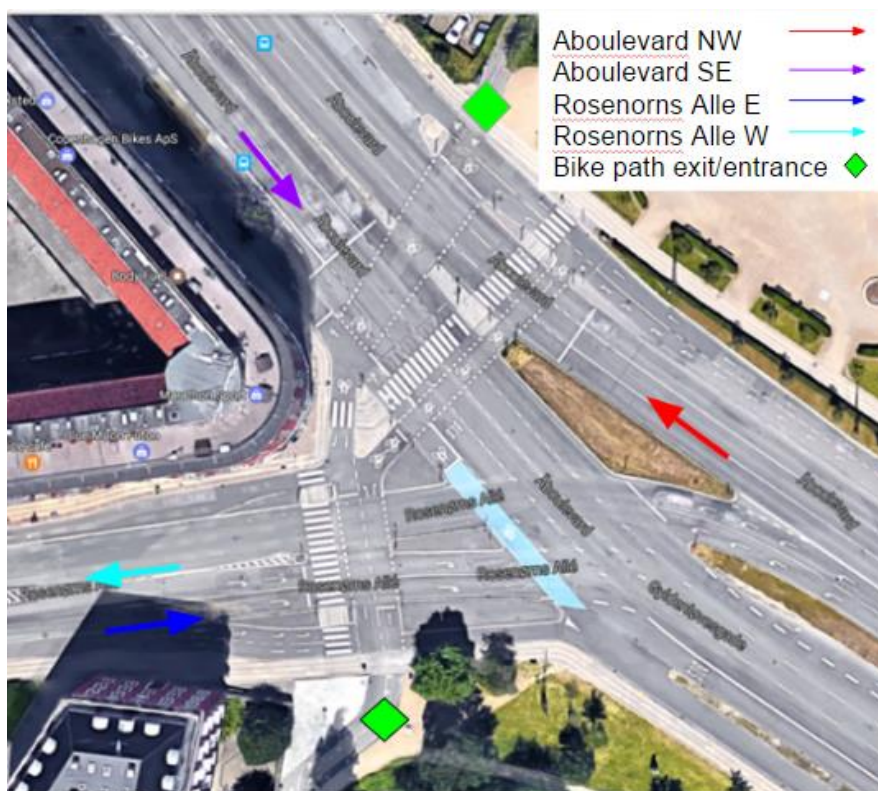


Figure 3: The Boulevard-Rosenorns Alle intersection with labeled directional traffic flow and bike path entrance/exit locations.

We gathered automobile, cyclist, and light timing data from morning and afternoon rush hours in order to construct models of each intersection during each rush hour period. Our goal was to implement strategies that would reduce bicycle congestion in each intersection. The impact of each strategy on overall traffic flow would be compared the traffic flow of the base intersection model. The strategies that were tested are described below:

1. Widening Bicycle Lanes: This strategy increased bicycle lanes in the intersection roads in two increments: 0.5 meters and 1 meter. The overall road width remained the same. Larger lanes mean increased bicycle flow through intersections.
2. Modifying Light Timings: By changing the light timings so that cyclists have more green time, bicycle traffic increases at the cost of automobile traffic. There are two variations of this strategy. The first variation is inverting the light timings of each road. This means that the light timing of one road replaces the light timings of the other road. The second variation was to increase the bicycle green time by 5 seconds. If one of the two intersection roads had significantly larger bicycle traffic, that road would receive the 5-second increase while the other road would not.
3. Allowing Cyclist Right Turn on Red: In the USA, cars are allowed to turn right at an intersection if it is safe to turn. Our team wanted to test if this change would increase traffic flow in bicycles. Interviewee responses indicated that cars should not be allowed to turn right due to safety concerns for cyclists. The first variation of this test was allowing cyclists to turn right if conditions were safe. The second variation involves building a right turn track for cyclists (shown in figure 4) so that cyclists turning right would not impede traffic.



Figure 4: Implementation of tracks for right turns – highlighted in red - for the Gothersgade-Øster Voldgade intersection (left) and the Dronning Louises Bro-Søtorvet intersection (right).

RESULTS

Here are the results from each strategy. Percent changes represent the increase or decrease in automobile or cyclist traffic compared to the original intersection model. Note that the third intersection, the Rosenorn Alle-Aboulevard intersection is not included in the results. I am still in the process of analyzing the simulations, but the results will be available before the interview date.

Table 1: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by increasing width of bicycle tracks by 0.5m.

| +0.5m | Current Population | | Future Population | |
|-------------------------------|--------------------|----------|-------------------|----------|
| | Motorists | Cyclists | Motorists | Cyclists |
| Gothersgade-Øster Voldgade | -0.71% | 1.05% | 3.23% | 3.52% |
| Dronning Louises Bro-Søtorvet | -1.40% | 2.59% | -3.40% | 2.72% |

Table 2: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by increasing width of bicycle tracks by 1.0m.

| +1.0m | Current Population | | Future Population | |
|-------|--------------------|----------|-------------------|----------|
| | Motorists | Cyclists | Motorists | Cyclists |
| | | | | |

| | | | | |
|-------------------------------|--------|-------|--------|-------|
| Gothersgade-Øster Voldgade | 1.46% | 1.91% | 1.12% | 6.95% |
| Dronning Louises Bro-Søtorvet | -4.32% | 9.22% | -2.44% | 6.35% |

Table 3: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by allowing cyclists to turn right during a red light.

| Right on Red | Current Population | | Future Population | |
|-------------------------------|--------------------|----------|-------------------|----------|
| | Motorists | Cyclists | Motorists | Cyclists |
| Gothersgade-Øster Voldgade | 0.63% | -8.66% | 1.27% | -5.21% |
| Dronning Louises Bro-Søtorvet | -3.38% | -14.65% | -3.75% | -15.81% |

Table 4: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by implementing a dedicated right turn track for cyclists.

| Right Turn Track | Current Population | | Future Population | |
|-------------------------------|--------------------|----------|-------------------|----------|
| | Motorists | Cyclists | Motorists | Cyclists |
| Gothersgade-Øster Voldgade | 5.29% | 2.87% | 1.48% | -0.74% |
| Dronning Louises Bro-Søtorvet | -3.36% | 3.93% | -1.20% | -0.09% |

Table 5: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by inverting traffic light timings.

| Inverting Traffic Lights | Current Population | | Future Population | |
|-------------------------------|--------------------|----------|-------------------|----------|
| | Motorists | Cyclists | Motorists | Cyclists |
| Gothersgade-Øster Voldgade | 3.06% | 0.38% | 4.32% | -5.25% |
| Dronning Louises Bro-Søtorvet | -12.20% | 10.00% | -18.42% | 11.71% |

Table 6: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by adding additional time for lanes.

| Additional Time (+5s) | Current Population | | Future Population | |
|---------------------------------------------------------|--------------------|----------|-------------------|----------|
| | Motorists | Cyclists | Motorists | Cyclists |
| Gothersgade-Øster Voldgade (Gothersgade prioritized) | 1.02% | 3.91% | -1.85% | 2.81% |
| Gothersgade-Øster Voldgade (Øster Voldgade prioritized) | 2.83% | -1.92% | 4.02% | -3.67% |
| Dronning Louises Bro-Søtorvet | -5.77% | 6.33% | -0.20% | 5.64% |

Table 7: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by increasing bicycle track widths and adding additional time.

| +0.5m & Additional Time | Current Population | | Future Population | |
|------------------------------------------------------------------|--------------------|----------|-------------------|----------|
| | Motorists | Cyclists | Motorists | Cyclists |
| Gothersgade-Øster Voldgade (Gothersgade prioritized) | -4.79% | -1.58% | -2.91% | 5.34% |
| Gothersgade-Øster Voldgade (Øster Voldgade prioritized) | 3.45% | -3.82% | 7.07% | -0.14% |
| Dronning Louises Bro-Søtorvet | -5.43% | 8.34% | -4.52% | 9.76% |

Rosenorn Alle-Aboulevard Intersection Results

The 3rd and final intersection analyzed was the Rosenorn Alle-Aboulevard intersection (figure 1). This intersection has a three-road merge, unlike other two intersections which classified under 4-legged. I chose to observe and analyze this intersection because of its unusual infrastructure and complex bicycle turning routes. The tables below show the results of the software simulations of this intersection.

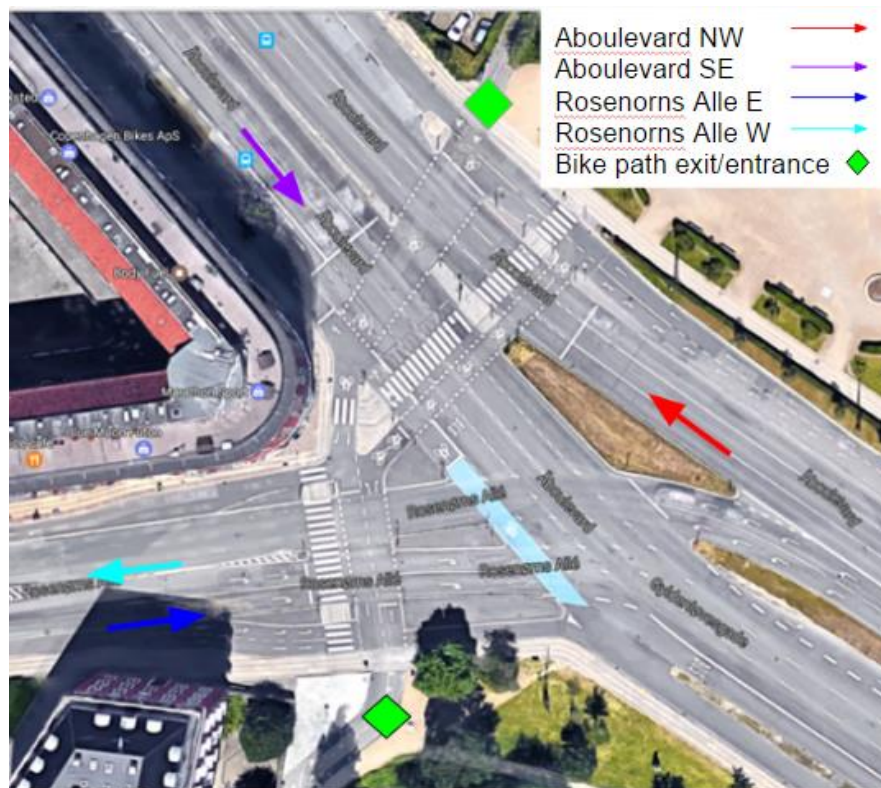


Figure 1: The Aboulevard-Rosenorns Alle intersection with labeled directional traffic flow and bike path entrance/exit locations.

I measured the number of automobiles and bicycles traveling in each direction of the base intersection simulation five times and calculated the average number of automobiles and bicycles traveling through the intersection. This measurement was repeated for each modified intersection simulation and I compared the average number of vehicles traveling through the modified intersection with the vehicles traveling through the base intersection. The tables below represent the overall changes in motorist and cyclist traffic flow through the intersection.

Table 1: Percentage change in number of cyclists and motorists travelling through the simulated intersection per hour by increasing width of bicycle tracks by 0.5m.

| +0.5m | Current Population | | Future Population | |
|-----------|--------------------|----------|-------------------|----------|
| | Motorists | Cyclists | Motorists | Cyclists |
| Morning | 0.67% | -1.96% | 1.12% | 6.95% |
| Afternoon | -6.29% | 2.53% | -1.84% | 2.61% |

Table 2: Percentage change in number of cyclists and motorists travelling through the simulated intersection per hour by increasing width of bicycle tracks by 1m.

| +1m | Current Population | | Future Population | |
|-----------|--------------------|----------|-------------------|----------|
| | Motorists | Cyclists | Motorists | Cyclists |
| Morning | 3.37% | 2.63% | -0.95% | 1.4% |
| Afternoon | -6.68% | 5.49% | -0.25% | 1.26% |

Table 3: Percentage change in number of cyclists and motorists travelling through the simulated intersection per hour by increasing green time of bicycles on either road by 5 seconds.

| Additional Time (+5s) | Current Population | | Future Population | |
|--------------------------|--------------------|----------|-------------------|----------|
| | Motorists | Cyclists | Motorists | Cyclists |
| Morning(Aboulevard) | 3.47% | 4.98% | -2.23% | 3.89% |

| | | | | |
|-----------------------|--------|-------|--------|--------|
| Afternoon(Aboulevard) | -2.86% | 5.61% | 0.05% | 2.23% |
| Morning(Rosenorn) | -2% | -3.2% | -0.87% | -2.64% |
| Afternoon(Rosenorn) | -4.68% | 2.62% | 2.8% | -1.18% |

Table 4: Percentage change in number of cyclists and motorists travelling through the simulated intersection per hour by increasing green time of bicycles on either road by 5 seconds and bicycle lane width by 0.5m.

| +0.5m & Additional Time (+5s) | Current Population | | Future Population | |
|-------------------------------------|--------------------|----------|-------------------|----------|
| | Motorists | Cyclists | Motorists | Cyclists |
| Morning(Aboulevard) | -0.14% | 4.15% | 0.65% | 3.88% |
| Afternoon(Aboulevard) | -4.9% | 4.17% | -0.54% | 5.39% |
| Morning(Rosenorn) | -1.33% | 0.53% | -2.9% | 0.08% |
| Afternoon(Rosenorn) | -4.2% | 5.43% | 0.14% | 4.89% |